CHAPTER 7

ELECTROMAGNETIC WAVES

7.1 INTRODUCTION

In this chapter, we concentrate on the fundamental properties of electromagnetic waves as they propagate in various types of media, and their interaction with matter. Following are the topics included in the chapter:

- Definition of EM waves
- Wave equations and solutions
- Propagation characteristics
- Waves in conductors and dielectrics
- Poynting vector and average power consideration in EM wave
- Polarisation: Linear, Circular, and elliptical polarization
- Normal and oblique incidence of EM waves
- Reflection and transmission coefficients
- Brewster angle

7.2 ELECTROMAGNETIC WAVES

In general, wave is a carrier of energy or information and is a function of time as well as space. As far as we are concerned, a wave means Electromagnetic wave (or simply EM wave). Some examples of EM waves are radio, radar wave (or simply EM wave). Some examples of EM waves are radio, radar beams and TV signals. Maxwell predicated the existence of EM waves and established it through his well-known Maxwell's equations.

7.2.1 General Wave Equation for Electromagnetic Waves

Consider a linear, homogeneous and isotropic medium. The three-dimensional vector wave equation or *Helmholtz equation* in an absorbing medium or lossy dielectric medium is defined as

$$\nabla^2 \boldsymbol{E} - \mu\varepsilon \frac{\partial^2 \boldsymbol{E}}{\partial t^2} - \mu\sigma \frac{\partial \boldsymbol{E}}{\partial t} = 0 \qquad ...(7.1)$$

$$\nabla^2 \boldsymbol{H} - \mu\varepsilon \frac{\partial^2 \boldsymbol{H}}{\partial t^2} - \mu\sigma \frac{\partial \boldsymbol{H}}{\partial t} = 0 \qquad ...(7.2)$$

Now, we will consider the modifications in the wave equations for different cases.

7.2.2 Wave Equation for Perfect Dielectric Medium

In a perfect dielectric medium, the conductivity is zero, i.e. $\sigma = 0$. Substituting it in equations (7.1) and (7.2) we get

$$\nabla^2 \boldsymbol{E} = \mu\varepsilon \frac{\partial^2 \boldsymbol{E}}{\partial t^2}$$

and

$$\nabla^2 H = \mu\varepsilon \frac{\partial^2 H}{\partial t^2}$$

These are the wave equations for perfect dielectric medium.

7.2.3 Wave Equation for Free Space

We have already studied the parameters of free space which are as follows :

1. Relative permittivity, $\varepsilon_r = 1$ (i.e. $\varepsilon = \varepsilon_0$)
2. Relative permeability, $\mu_r = 1$ (i.e. $\mu = \mu_0$)
3. Conductivity, $\sigma = 0$

Substituting these parameters in equations (7.1) and (7.2) we get

$$\nabla^2 E = \mu_0\varepsilon_0 \frac{\partial^2 E}{\partial t^2}$$

and

$$\nabla^2 H = \mu_0\varepsilon_0 \frac{\partial^2 H}{\partial t^2}$$

These are the wave equations for free space

7.2.4 Wave Equation for Time-Harmonic Fields

The standard form of wave equations for time harmonic fields (in phasor form) are defined as

$$\nabla^2 E_S - \gamma^2 E_S = 0$$

and

$$\nabla^2 H_S - \gamma^2 H_S = 0$$

where γ is a complex constant called the propagation constant.

Propagation Constant

For a medium with permittivity ε, permeability μ, and conductivity σ, the propagation constant is given by

$$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)}$$

Propagation constant is expressed in per meter (m^{-1}). It can be also defined as

$$\gamma = \alpha + j\beta$$

where α is the attenuation constant, and β is the phase constant as described below.

1. **Attenuation Constant (α):** The real part of the propagation constant is defined as the attenuation constant (α). The attenuation constant defines the rate at which the fields of the wave are attenuated as the wave propagates. Its unit is Neper per metre.

2. **Phase Constant (β):** The imaginary part of the propagation constant is defined as the phase constant (β). The phase constant defines the rate at which the phase changes as the wave propagates. Its unit is radian per metre.

7.3 UNIFORM PLANE WAVES

The uniform plane wave has two important words in it; uniform and plane.

1. **Plane:** The term plane means that the electric and magnetic field vectors both lie in a plane and all such planes are parallel. In addition, the phase of the wave is constant over a plane.
2. **Uniform:** The word uniform means, the amplitude and phase of vectors E and H are constant over the planes.

In Figure 7.1, we have chosen the electric field to be in x-direction and the magnetic field will turn out to be orthogonal to x-direction and so is directed in the y-direction. The field vectors E and H are in the x-y plane and are plane waves. The word uniform, also means that the field vectors are independent of x and y in these planes. Thus, the vector fields E and H can only be functions of z and time, i.e.

$$E = E_x(z, t)\, a_x \qquad ...(7.3)$$

$$H = H_y(z, t)\, a_y \qquad ...(7.4)$$

The wave associated with these field vectors propagates in the z-directions as illustrated in Figure.

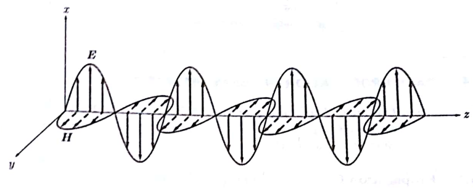

Figure 7.1 Propagation of a Uniform Plane Wave

Inserting the time factor $e^{j\omega t}$ into above equations, we get the instantaneous form of the field components as

$$E(z, t) = \text{Re}[(E_0 e^{-\gamma z} e^{j\omega t})\, a_x]$$

$$H(z, t) = \text{Re}[(H_0 e^{-\gamma z} e^{j\omega t})\, a_y]$$

The magnitude E_0 and H_0 of the field components are related as

$$H_0 = \frac{E_0}{\eta}$$

where η is *intrinsic impedance* of the medium. Following are some important points related to uniform plane waves.

POINTS TO REMEMBER

1. In general, if a_E, a_H and a_k are unit vectors along the E field, the H field and the direction of wave propagation; it can be shown that

$$a_k \times a_E = a_H$$
$$a_H \times a_k = a_E$$
$$a_E \times a_H = a_k$$

i.e., both E and H fields (or EM waves) are everywhere normal to the direction of wave propagation, a_k.

2. An electromagnetic wave which has no electric or magnetic field components in the direction of propagation (i.e., all components of E and H are perpendicular to the direction of propagation) is called a transverse electromagnetic (TEM) wave. All plane waves are TEM waves.

3. For a uniform plane wave propagating in $+\boldsymbol{a}_z$ direction, the field components are

$$\boldsymbol{E}(z,t) = \text{Re}[(E_0 e^{-\gamma z} e^{j\omega t})\boldsymbol{a}_x]$$
$$\boldsymbol{H}(z,t) = \text{Re}[(H_0 e^{-\gamma z} e^{j\omega t})\boldsymbol{a}_y]$$

If the uniform plane wave is propagating in $-\boldsymbol{a}_z$ direction, then the field components are given by

$$\boldsymbol{E}(z,t) = \text{Re}[(E_0 e^{\gamma z} e^{j\omega t})\boldsymbol{a}_x]$$
$$\boldsymbol{H}(z,t) = \text{Re}[(H_0 e^{\gamma z} e^{j\omega t})\boldsymbol{a}_y]$$

Here, we must notice that for wave propagating in $\boldsymbol{a}_z$ direction, fields consist the term $e^{-\gamma z}$ whereas for the wave propagating in $-\boldsymbol{a}_z$ direction, fields consist the term $e^{\gamma z}$.

7.4 WAVE PROPAGATION IN LOSSY DIELECTRICS

Consider a uniform plane wave travelling in a medium where the conductivity is nonzero, $(\sigma \neq 0)$, that is, a lossy medium. Let us study the various characteristics of the plane waves in the medium.

7.4.1 Propagation Constant in Lossy Dielectrics

We have already defined the propagation constant as

$$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)}$$

and

$$\gamma = \alpha + j\beta$$

Solving the above two equations, we obtain the attenuation constant (α) and phase constant β as

$$\alpha = \omega\sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1+\frac{\sigma^2}{\omega^2\varepsilon^2}} - 1\right]} \quad \text{...(7.5)}$$

and

$$\beta = \omega\sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1+\frac{\sigma^2}{\omega^2\varepsilon^2}} + 1\right]} \quad \text{...(7.6)}$$

Thus, α and β are both nonzero for the medium and hence, the propagation constant, γ includes both imaginary and real parts.

7.4.2 Solution of Uniform Plane Wave Equations in Lossy Dielectrics

We have the field components of the wave propagating along $\boldsymbol{a}_z$ direction as

$$\boldsymbol{E}(z,t) = \text{Re}\left[(E_0 e^{-\gamma z} e^{j\omega t})\boldsymbol{a}_x\right] \quad \text{...(7.7)}$$

and

$$\boldsymbol{H}(z,t) = \text{Re}\left[(H_0 e^{-\gamma z} e^{j\omega t})\boldsymbol{a}_y\right] \quad \text{...(7.8)}$$

Substituting $\gamma = \alpha + j\beta$ in equation (7.7), we get

$$\boldsymbol{E}(z,t) = \text{Re}\left[E_0 e^{-\alpha z} e^{j(\omega t - \beta z)}\boldsymbol{a}_x\right]$$

or

$$\boldsymbol{E}(z,t) = E_0 e^{-\alpha z}\cos(\omega t - \beta z)\boldsymbol{a}_x$$

Similarly, the magnetic field component is obtained as

$$\boldsymbol{H}(z,t) = \text{Re}\left[H_0 e^{-\alpha z} e^{j(\omega t - \beta z)}\boldsymbol{a}_y\right]$$

or

$$\boldsymbol{H}(z,t) = H_0 e^{-\alpha z}\cos(\omega t - \beta z)\boldsymbol{a}_y$$

Here, $E_0 e^{-\alpha z}$ is the instantaneous amplitude of electric field, $H_0 e^{-\alpha z}$ is the instantaneous amplitude of magnetic field and $(\omega t - \beta z)$ is the instantaneous phase angle of the wave.

7.4.3 Velocity of Wave Propagation in Lossy Dielectrics

The velocity at which a fixed point on the wave travelling is called velocity of wave propagation. Let us consider a fixed point P on the wave $A\sin(\omega t - \beta z)$, i.e.

$$\omega t - \beta z = \text{constant}$$

As the wave advances with time, point P moves along $+\boldsymbol{a}_z$ direction. Differentiating both sides with respect to time, we get

$$\omega - \beta\frac{dz}{dt} = 0$$

or

$$\frac{dz}{dt} = \frac{\omega}{\beta}$$

or

$$v_p = \frac{\omega}{\beta} \quad \text{...(7.9)}$$

where v_p gives the velocity of fixed point P on the wave which is called the velocity of wave propagation.

7.4.4 Wavelength of Propagating Wave

The wavelength of the propagating wave can be given as

$$\lambda = v_p T$$

where v_p is the velocity of wave propagation, and T is the time period of the wave. So, substituting equation (7.9) we get

$$\lambda = \left(\frac{\omega}{\beta}\right)T = \left(\frac{2\pi/T}{\beta}\right)T$$

or

$$\lambda = \frac{2\pi}{\beta}$$

7.4.5 Intrinsic Impedance

Consider a uniform plane wave travelling in $+\boldsymbol{a}_z$ direction with field components

$$\boldsymbol{E}_s = E_0 e^{-\gamma z}\boldsymbol{a}_x \quad \text{...(7.10)}$$

and

$$\boldsymbol{H}_s = H_0 e^{-\gamma z}\boldsymbol{a}_y \quad \text{...(7.11)}$$

The ratio E_0/H_0 is called intrinsic impedance and denoted by η, i.e.

$$\eta = \frac{E_0}{H_0}$$

Solving equations (7.10) and (7.11) using Maxwell's equation, we get

$$\eta = \frac{j\omega\mu}{\gamma} = \frac{j\omega\mu}{\sqrt{j\omega\mu(\sigma + j\omega\varepsilon)}}$$

or

$$\eta = \sqrt{\frac{j\omega\mu}{(\sigma + j\omega\varepsilon)}} \quad \text{...(7.12)}$$

Thus, the intrinsic impedance is a complex quantity. Its unit is ohm (Ω). It can be also expressed as

$$\eta = |\eta|\underline{/\theta_\eta} = |\eta|e^{j\theta_\eta}$$

with

$$|\eta| = \frac{\sqrt{\mu/\varepsilon}}{\left[1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2\right]^{1/4}}$$

and

$$\tan 2\theta_\eta = \frac{\sigma}{\omega\varepsilon}$$

7.4.6 Loss Tangent

For a time-harmonic field, we have the Maxwell's equation,

$$\nabla \times \boldsymbol{H} = (\sigma + j\omega\varepsilon)\boldsymbol{E}$$

$$= j\omega\varepsilon\left[1 - j\frac{\sigma}{\omega\varepsilon}\right]E_s$$

$$= j\omega\varepsilon_c E_s$$

where ε_c is the complex permittivity given by,

$$\varepsilon_c = \varepsilon\left[1 - j\frac{\sigma}{\omega\varepsilon}\right]$$

or

$$\varepsilon_c = (\varepsilon' - j\varepsilon'')$$

where (ε') is the real part and (ε'') is the imaginary part of the complex permittivity. The ratio of (ε'') to (ε') is the ratio of the magnitude of the conduction current density to the magnitude of the displacement current density. This ratio is defined as the loss tangent or loss angle of the medium, i.e.

$$\left|\frac{\varepsilon''}{\varepsilon'}\right| = \frac{\sigma}{\omega\varepsilon} = \frac{|\sigma E_s|}{|\omega\varepsilon E_s|} = \frac{|J_{\text{conduction}}|}{|J_{\text{displacement}}|} = \tan\theta$$

where $\tan\theta$ is the *loss tangent* and θ is the *loss angle*. The loss tangent gives a measure of how lossy a medium is. For a lossy dielectric, loss tangent is of the order of unity.

7.5 WAVE PROPAGATION IN LOSSLESS DIELECTRICS

A lossless dielectric is one in which $\sigma << \omega\varepsilon$. So, for lossless dielectrics the medium parameters may be considered as

$$\sigma \simeq 0, \qquad \varepsilon = \varepsilon_0\varepsilon_r \qquad \mu = \mu_0\mu_r$$

The propagation characteristics of the lossless dielectrics are obtained as follows:

7.5.1 Attenuation Constant

From equation (7.5), we have the attenuation constant

$$\alpha = \omega\sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1+\frac{\sigma^2}{\omega^2\varepsilon^2}} - 1\right]}$$

Substituting $\sigma = 0$ in the above equation we get the attenuation constant in a lossless dielectric medium as

$$\alpha = 0 \qquad \text{...(7.13)}$$

7.5.2 Phase Constant

From equation (7.6), we have the phase constant

$$\beta = \omega\sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1+\frac{\sigma^2}{\omega^2\varepsilon^2}} + 1\right]}$$

Substituting $\sigma = 0$ in the above equation we get the phase constant in a lossless dielectric medium as

$$\beta = \omega\sqrt{\mu\varepsilon} \qquad \text{...(7.14)}$$

7.5.3 Propagation Constant

Propagation constant in a medium is defined by

$$\gamma = \alpha + j\beta$$

Substituting α and β from equations (7.13) and (7.14), we get the propagation constant in the lossless dielectric medium as

$$\gamma = j\omega\sqrt{\mu\varepsilon}$$

7.5.4 Velocity of Wave Propagation

The velocity of wave propagation in a medium is given by

$$v_p = \frac{\omega}{\beta}$$

Substituting β from equation (7.14), we get the velocity of wave propagation in the lossless dielectric medium as

$$v_p = \frac{\omega}{\omega\sqrt{\mu\varepsilon}} = \frac{1}{\sqrt{\mu\varepsilon}}$$

7.5.5 Intrinsic Impedance

From equation (7.12), we have the intrinsic impedance

$$\eta = \sqrt{\frac{j\omega\mu}{(\sigma + j\omega\varepsilon)}}$$

Substituting $\sigma = 0$ in the above equation we get the intrinsic impedance in a lossless dielectric medium as

$$\eta = \sqrt{\frac{\mu}{\varepsilon}}$$

7.5.6 Field Components of Uniform Plane Wave in Lossless Dielectric

Since, the field components of uniform plane wave in lossy dielectric is given by

$$E(z,t) = E_0 e^{-\alpha z}\cos(\omega t - \beta z)\,a_x$$

and

$$H(z,t) = H_0 e^{-\alpha z}\cos(\omega t - \beta z)\,a_y$$

So, by substituting $\alpha = 0$ in above equations, we get the field components in lossless dielectric as

$$E = E_0\cos(\omega t - \beta z)\,a_x$$

$$H = H_0\cos(\omega t - \beta y)\,a_x$$

where E_0 and H_0 are related as

$$\frac{E_0}{H_0} = \eta = \sqrt{\frac{\mu}{\varepsilon}}$$

Thus, we see that for a lossless dielectric medium, the wave propagates without any attenuation, and the electric and magnetic fields are in phase with each other.

7.6 WAVE PROPAGATION IN PERFECT CONDUCTORS

A perfect, or good conductor, is one in which $\sigma >> \omega\varepsilon$. So, for good conductors the medium parameters may be considered as

$$\sigma \simeq \infty, \qquad \varepsilon = \varepsilon_0, \qquad \mu = \mu_0\mu_r$$

The propagation characteristics of good conductors are obtained as follows :

7.6.1 Attenuation Constant

From equation (7.5), we have the attenuation constant

$$\alpha = \omega\sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1+\frac{\sigma^2}{\omega^2\varepsilon^2}} - 1\right]}$$

Here, the condition is, $\sigma \gg \omega\varepsilon$, so we get

$$\alpha = \sqrt{\frac{\omega\mu\sigma}{2}} \qquad \text{...(7.15)}$$

7.6.2 Phase Constant

From equation (7.6), we have the phase constant

$$\beta = \omega\sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1+\frac{\sigma^2}{\omega^2\varepsilon^2}}+1\right]}.$$

Again, applying the condition $\sigma \gg \omega\varepsilon$ in above equation, we get the phase constant in a good conductor as

$$\beta = \sqrt{\frac{\omega\mu\sigma}{2}} \qquad ...(7.16)$$

7.6.3 Propagation Constant

Propagation constant in a medium is defined as

$$\gamma = \alpha + j\beta$$

Substituting α and β from equations (7.15) and (7.16), we get the propagation constant in the good conductors as

$$\gamma = \sqrt{\frac{\omega\mu\sigma}{2}} + j\sqrt{\frac{\omega\mu\sigma}{2}}$$

7.6.4 Velocity of Wave Propagation

The velocity of wave propagation in a medium is given by

$$v_p = \frac{\omega}{\beta}$$

Substituting β from equation (7.16), we get the velocity of wave propagation in a good conductor as

$$v_p = \frac{\omega}{\sqrt{\frac{\omega\mu\sigma}{2}}} = \sqrt{\frac{2\omega}{\mu\sigma}}$$

7.6.5 Intrinsic Impedance

From equation (7.12), we have the intrinsic impedance

$$\eta = \sqrt{\frac{j\omega\mu}{(\sigma + j\omega\varepsilon)}} = \sqrt{\frac{j\omega\mu}{\sigma(1+\frac{j\omega\varepsilon}{\sigma})}}$$

Since, $\sigma \gg \omega\varepsilon$, i.e. $\frac{\omega\varepsilon}{\sigma} \ll 1$. So, we can write

$$1 + \frac{j\omega\varepsilon}{\sigma} \backsimeq 1$$

Hence, the intrinsic impedance in a good conductor reduces is obtained as

$$\eta = \sqrt{\frac{j\omega\mu}{\sigma}}$$

7.6.6 Skin Effect

When an AC current is applied to the conductors, it shows skin effect. It is the tendency of an alternating electric current to distribute itself within a conductor in such a way that the current density is the largest near the surface of the conductor, while decreasing at greater depths. Mathematically, skin effect is expressed by skin depth.

Skin Depth

It is defined as the depth in which the magnitude of the wave is attenuated to e^{-1} ($= 37\%$) of its original value. The electric field of a propagating wave in a good conductor in $\boldsymbol{a}_z$ direction is given by

$$E = E_0 e^{-\alpha z}\cos(\omega t - \beta z)\,\boldsymbol{a}_z$$

where $E_0 e^{-\alpha z}$ is the instantaneous amplitude of the field. So, after travelling a distance $z = \delta$, the field reduces to

$$E = E_0 e^{-\alpha\delta} \qquad ...(7.17)$$

Now, from definition of skin depth, the electric field of uniform plane wave after traveling a distance δ (skin depth) reduces to e^{-1} of its original value. i.e.

$$E = E_0 e^{-1} \qquad ...(7.18)$$

So, from equations (7.17) and (7.18) we get

$$\alpha\delta = 1$$

or

$$\delta = \frac{1}{\alpha}$$

Substituting equations (7.15), we get

$$\delta = \frac{1}{\alpha} = \sqrt{\frac{2}{\omega\mu\sigma}}$$

Thus, in a good conductor, the depth of penetration decreases with increasing frequency (ω).

7.7 WAVE PROPAGATION IN FREE SPACE

In free space, we have the parameters

$$\sigma \simeq 0, \qquad \varepsilon = \varepsilon_0 \qquad \mu = \mu_0$$

The propagation characteristics in free space are obtained as follows.

7.7.1 Attenuation Constant

From equation (7.5), we have the attenuation constant in a medium

$$\alpha = \omega\sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1+\frac{\sigma^2}{\omega^2\varepsilon^2}}-1\right]} \qquad ...(7.19)$$

Substituting $\sigma = 0$ in the above equation we get the attenuation constant in a lossless dielectric medium as

$$\alpha = 0$$

7.7.2 Phase Constant

From equation (7.6), we have the phase constant in a medium

$$\beta = \omega\sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1+\frac{\sigma^2}{\omega^2\varepsilon^2}}+1\right]} \qquad ...(7.20)$$

Substituting $\sigma = 0$, $\varepsilon = \varepsilon_0$ and $\mu = \mu_0$ in the above equation we get the phase constant in free space as

$$\beta = \omega\sqrt{\mu_0\varepsilon_0}$$

7.7.3 Propagation Constant

Propagation constant in a medium is defined by

$$\gamma = \alpha + j\beta$$

Substituting α and β from equations (7.19) and (7.20), we get the propagation constant in the free space as

$$\gamma = j\omega\sqrt{\mu_0\varepsilon_0}$$

7.7.4 Velocity of Wave Propagation

The velocity of wave propagation is given by

$$v_p = \frac{\omega}{\beta}$$

Substituting β from equation (7.20), we get the velocity of wave propagation in the free space as

$$v_p = \frac{\omega}{\omega\sqrt{\mu_0\varepsilon_0}} = \frac{1}{\sqrt{\mu_0\varepsilon_0}} = 3\times10^8\text{m/s}$$

Hence, the velocity of EM wave in free space is same as the velocity of light ($c = 3\times10^8$m/s) in free space.

7.7.5 Intrinsic Impedance

From equation (7.12), we have the intrinsic impedance

$$\eta = \sqrt{\frac{j\omega\mu}{(\sigma + j\omega\varepsilon)}}$$

Substituting $\sigma = 0$, $\varepsilon = \varepsilon_0$, and $\mu = \mu_0$ in the above equation, we get the intrinsic impedance in free space as

$$\eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 120\pi \approx 377\,\Omega$$

7.7.6 Field Components of Uniform Plane Wave in Free Space

We have field components of uniform plane wave in lossy dielectric as

$$\boldsymbol{E}(z,t) = E_0e^{-\alpha z}\cos(\omega t - \beta z)\boldsymbol{a}_x$$

and

$$\boldsymbol{H}(z,t) = H_0e^{-\alpha z}\cos(\omega t - \beta z)\boldsymbol{a}_y$$

Since, in free space attenuation constant, $\alpha = 0$. So, the field components reduces to

$$\boldsymbol{E} = E_0\cos(\omega t - \beta z)\boldsymbol{a}_x$$

$$\boldsymbol{H} = H_0\cos(\omega t - \beta y)\boldsymbol{a}_z$$

These are the field components of uniform plane wave propagating in free space, where E_0 and H_0 are related as

$$\frac{E_0}{H_0} = \eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}$$

Thus, we see that in free space, the wave propagates without any attenuation and the electric and magnetic fields are in phase with each other.

7.8 POWER CONSIDERATION IN ELECTROMAGNETIC WAVES

One of the important characteristics of electromagnetic wave is that it can transfer energy from one point to another. The law of conservation of energy as applied to the electromagnetic fields is mathematically expressed by Poynting's theorem.

7.8.1 Poynting's Theorem

According to Poynting's theorem, at any point in an electromagnetic field, the power per unit area is described by a vector termed as Poynting vector which is basically a curl of electric field intensity vector and magnetic field intensity vector. i.e.

$$\boldsymbol{\mathcal{P}} = \boldsymbol{E}\times\boldsymbol{H}$$

The magnitude of Poynting vector ($\boldsymbol{\mathcal{P}}$) is the power flow per unit area, and it points along the direction of wave propagation vector. Its unit is watt per squared meter (W/m^2). For time harmonic field, the phasor of Poynting vector is defined as

$$\boldsymbol{\mathcal{P}}_s = \boldsymbol{E}_s\times\boldsymbol{H}_s^* \qquad ...(7.21)$$

where the asterisk (*) sign in the magnetic field vector represents the complex conjugate of the vector. This is the instantaneous power in uniform plane wave also called the *complex Poynting vector*.

7.8.2 Average Power Flow in Uniform Plane Waves

To determine the time-average power flow in a uniform plane wave, we integrate equation (7.21) over the time-period T. i.e.

$$\boldsymbol{\mathcal{P}}_{av} = \frac{1}{T}\int_0^T \boldsymbol{\mathcal{P}}_s\,dt$$

or

$$\boldsymbol{\mathcal{P}}_{av} = \frac{1}{T}\int_0^T(\boldsymbol{E}_s\times\boldsymbol{H}_s^*)\,dt$$

This is equivalent to

$$\boldsymbol{\mathcal{P}}_{av} = \frac{1}{2}\text{Re}[\boldsymbol{E}_s\times\boldsymbol{H}_s^*]$$

$\boldsymbol{\mathcal{P}}_{av}$ is the time-average power density vector in a uniform plane wave which is expressed in Watt per squared meter (W/m^2). The total time-average power passing through a surface S is given by

$$P_{av} = \int_S \boldsymbol{\mathcal{P}}_{av}\cdot d\boldsymbol{S}$$

Let us generalize this expression for lossy and lossless dielectric media.

Average Poynting Vector in Lossless Dielectric Medium

For a uniform plane wave propagating in a lossless medium in $\boldsymbol{a}_z$ direction, we have the field components

$$\boldsymbol{E}_s = E_0e^{-j\beta z}\boldsymbol{a}_x$$

and

$$\boldsymbol{H}_s = \frac{E_0}{\eta}e^{-j\beta z}\boldsymbol{a}_y$$

Hence, the time-average Poynting vector in the field is

$$\boldsymbol{P}_{av} = \frac{1}{2}\text{Re}[\boldsymbol{E}_s\times\boldsymbol{H}_s^*]$$

$$= \frac{1}{2}\text{Re}\left[(E_0e^{-j\beta z}\boldsymbol{a}_x)\times\left(\frac{E_0}{\eta}e^{j\beta z}\boldsymbol{a}_y\right)\right] = \frac{E_0^2}{2\eta}\boldsymbol{a}_z$$

Similarly, we can also obtain the average Poynting vector in terms of magnetic field as

$$\boldsymbol{P}_{av} = \frac{\eta H_0^2}{2}\boldsymbol{a}_z$$

Average Poynting Vector in Lossy Dielectric Medium

Let us consider a uniform plane wave in a lossy dielectric medium. The phasor fields written in the vector form are

$$\boldsymbol{E}_s = E_0e^{-\alpha z}e^{-j\beta z}\boldsymbol{a}_x$$

$$\boldsymbol{H}_s = \frac{E_0}{|\eta|}e^{-\alpha z}e^{-j\beta z}e^{-j\theta_\eta}\boldsymbol{a}_y$$

So, the average Poynting vector in the uniform plane wave is

$$\boldsymbol{P}_{av} = \frac{1}{2}\text{Re}(\boldsymbol{E}_s\times\boldsymbol{H}_s^*)$$

$$= \frac{1}{2}\text{Re}\left[(E_0e^{-\alpha z}e^{-j\beta z}\boldsymbol{a}_x)\times\left(\frac{E_0}{|\eta|}e^{-\alpha z}e^{j\beta z}e^{j\theta_\eta}\boldsymbol{a}_y\right)\right]$$

$$= \frac{E_0^2}{2|\eta|} e^{-2\alpha z} \cos(\theta_\eta)\, \boldsymbol{a}_z$$

The average power in the wave contains the factor $e^{-2\alpha z}$, which says that the power is being dissipated in the medium as the wave passes through it.

7.9 WAVE POLARIZATION

Wave polarization is the electric field vector orientation as a function of time, at a fixed point in space. The three important types of polarization are (1) Linear, (2) Elliptical, and (3) Circular polarization.

7.9.1 Linear Polarization

A wave is said to be linearly polarised if the electric field remains along a straight line as a function of time at some point in the medium. For the wave propagation in $+\boldsymbol{a}_z$ direction, the linear polarized wave would in general have its electric field phasor expressed as

$$\boldsymbol{E}_s = (E_{x0}\,\boldsymbol{a}_x + E_{y0}\,\boldsymbol{a}_y) e^{-\alpha z} e^{-j\beta z}$$

where E_{x0} and E_{y0} are constant amplitudes along x and y. As the x and y -components of electric field are in same phase, so it is a *linearly polarized wave*. In general, for the wave traveling between different media, linear polarization may be of following two types:

1. **Parallel Polarisation:** It is defined as the polarisation in which the electric field of the wave is parallel to the plane of incidence. Parallel polarisation is also called vertical polarisation.
2. **Perpendicular Polarisation:** It is defined as the polarisation in which the electric field of the wave is perpendicular to the plane of incidence. Perpendicular polarisation is also called horizontal polarisation.

7.9.2 Elliptical Polarization

In elliptical polarized wave, the tip of the electric field vector traces out an elliptical locus in space. For the wave propagation in $+\boldsymbol{a}_z$ direction, the elliptical polarized wave would in general have its electric field phasor expressed as

$$\boldsymbol{E}_s = (E_{x0}\,\boldsymbol{a}_x + E_{y0}\, e^{j\phi}\,\boldsymbol{a}_y) e^{-\alpha z} e^{-j\beta z}$$

where ϕ is the phase difference between the x and y-components of electric field vector such that $0 < \phi < \pi/2$.

7.9.3 Circular Polarization

A circularly polarised wave is one in which the tip of the electric field vector $\boldsymbol{E}$ traces a circle as time varies. This is the special case of elliptically polarized wave. Here, the amplitude of x and y-components of electric field vector are equal (i.e. $E_{x0} = E_{y0} = E_0$) and phase difference between them is $\pi/2$ (i.e. $\phi = \pm\pi/2$). Thus, electric field phasor of circular polarized wave is expressed in general form as

$$\boldsymbol{E}_s = (E_0\,\boldsymbol{a}_x + E_0\, e^{\pm j\pi/2}\,\boldsymbol{a}_y) e^{-\alpha z} e^{-j\beta z}$$

In time domain, we may express the electric field vector of circular polarized wave as

$$\boldsymbol{E}(t) = E_0 \cos\omega t\, \boldsymbol{a}_x + E_0 \cos(\omega t \pm \pi/2)\, \boldsymbol{a}_y$$

Circular polarization may be of the following two types:

1. Right-hand Circular Polarization

When E_x leads E_y by $\pi/2$ (i.e. $\phi = -\pi/2$), we obtain the x and y-components of electric field vector as

$$E_x = E_0 \cos\omega t \text{ and } E_y = E_0 \sin\omega t$$

The instantaneous angle that $\boldsymbol{E}$ makes with the x-axis is given by

$$\theta = \tan^{-1}\left(\frac{E_y}{E_x}\right) = \omega t$$

This indicates that electric field vector ($\boldsymbol{E}$) rotates at a uniform rate with an angular velocity ω in a counterclockwise direction as shown in Figure 7.2(a). When the fingers of the right hand follow the direction of the rotation of $\boldsymbol{E}$, the thumb points to the direction of propagation of the wave. Thus, it is a *right-hand* or *positive circularly polarized wave*.

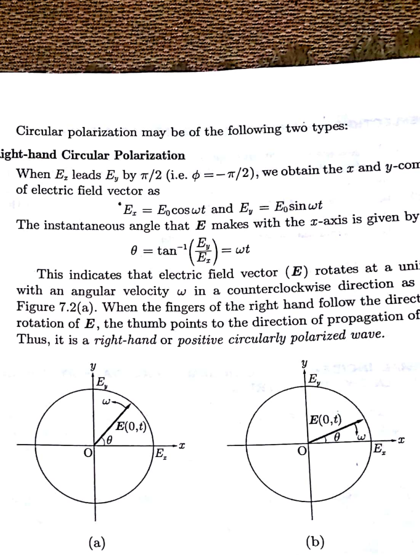

Figure 7.2: Illustration of Circular Polarization (a) Right-hand Circular Polarization, (b) Left-hand Circular Polarization

2. Left-hand Circular Polarization

When E_x lags E_y by $\pi/2$ (i.e. $\phi = \pi/2$), we obtain the x and y-components of electric field vector of circular polarized wave as

$$E_x = E_0 \cos\omega t \text{ and } E_y = -E_{y0} \sin\omega t$$

The instantaneous angle that $\boldsymbol{E}$ makes with the x-axis is given by

$$\theta = \tan^{-1}\left(\frac{E_y}{E_x}\right) = -\omega t$$

This indicates that electric field vector ($\boldsymbol{E}$) rotates at a uniform rate with an angular velocity ω in a clockwise direction as shown in Figure 7.2(b). When the fingers of the left hand follow the direction of the rotation of $\boldsymbol{E}$, the thumb points to the direction of propagation of the wave. Thus, it is a *left-hand* or *negative circularly polarized wave*.

POINTS TO REMEMBER

1. For a linearly polarized wave, the x and y-components of electric field are in same phase.
2. For an elliptical polarized wave, the x and y-components of electric field have the phase difference $0 < \phi < \pi/2$.
3. For a circular polarized wave, the x and y-components of electric field have the equal amplitude (i.e. $E_{x0} = E_{y0} = E_0$) and phase difference between them is $\pi/2$ (i.e. $\phi = \pm\pi/2$).

7.10 REFLECTION & REFRACTION OF UNIFORM PLANE WAVES

When a plane wave propagating in a homogeneous medium encounters an interface with a different medium, a portion of the wave is reflected from the interface while the remainder of the wave is transmitted. Depending upon the manner in which the uniform plane wave is incident on the boundary, two types of incidences may occur:

1. **Normal Incidence:** When a uniform plane wave is incident normally to the boundary between the media, it is known as normal incidence.
2. **Oblique incidence:** When a uniform plane wave is incident obliquely (making an angle other than 90°) to the boundary between the two media, it is known as oblique incidence.

In the following section, we will consider these two types of incidences at various media interfaces.

7.11 NORMAL INCIDENCE OF UNIFORM PLANE WAVE AT THE INTERFACE BETWEEN TWO DIELECTRICS

Consider a plane wave propagation along the $+\boldsymbol{a}_z$ direction incident normally on the boundary $z=0$ between medium 1 $(z<0)$ characterized by σ_1, ε_1, μ_1 and medium $2(z>0)$ characterized by σ_2, ε_2, μ_2, as shown in Figure 7.3.

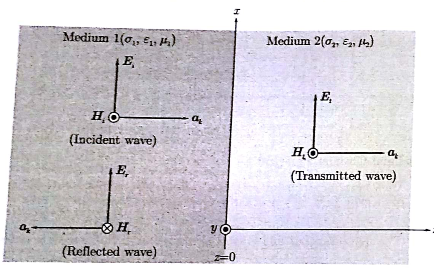

Figure 7.3: Normal Incidence of Uniform Plane Wave at the Interface between Two Dielectrics

In general, the field components of incident, reflected, and transmitted waves are expressed as given in table below.

Table 7.1: Representation of Field Components of Incident, Reflected, and Transmitted Wave for Interface between Two Dielectrics

	Electric field Components	Magnetic field components
Incident wave	$\boldsymbol{E}_{is}(z)=E_{i0}e^{-\gamma_1 z}\boldsymbol{a}_x$	$\boldsymbol{H}_{is}(z)=H_{i0}e^{-\gamma_1 z}\boldsymbol{a}_y=\frac{E_{i0}}{\eta_1}e^{-\gamma_1 z}\boldsymbol{a}_y$
Reflected wave	$\boldsymbol{E}_{rs}(z)=E_{r0}e^{\gamma_1 z}\boldsymbol{a}_x$	$\boldsymbol{H}_{rs}(z)=H_{r0}e^{\gamma_1 z}(-\boldsymbol{a}_y)=-\frac{E_{r0}}{\eta_1}e^{\gamma_1 z}\boldsymbol{a}_y$
Transmitted wave	$\boldsymbol{E}_{ts}(z)=E_{t0}e^{-\gamma_2 z}\boldsymbol{a}_x$	$\boldsymbol{H}_{ts}(z)=H_{t0}e^{-\gamma_2 z}\boldsymbol{a}_y=\frac{E_{t0}}{\eta_2}e^{-\gamma_2 z}\boldsymbol{a}_y$

7.11.1 Reflection and Transmission Coefficients

The ratio E_{r0}/E_{i0} is called *reflection coefficient* denoted by Γ and given by

$$\Gamma=\frac{E_{ro}}{E_{io}}=\frac{\eta_2-\eta_1}{\eta_2+\eta_1}$$

The ratio E_{t0}/E_{i0} is called *transmission coefficient* denoted by τ and given by

$$\tau=\frac{E_{to}}{E_{io}}=\frac{2\eta_2}{\eta_2+\eta_1}$$

7.11.2 Standing Wave Ratio

The total electric field intensity in medium 1 is the sum of the electric fields of the incident and reflected waves, i.e.

$$\boldsymbol{E}_{1s}(z)=\boldsymbol{E}_{is}(z)+\boldsymbol{E}_{rs}(z)$$

The ratio of the maximum amplitude to the minimum of the total electric field $|E_1|$ is called *standing wave ratio*, i.e.

$$s=\frac{|E_1|_{\max}}{|E_1|_{\min}}=\frac{1+|\Gamma|}{1-|\Gamma|}$$

POINTS TO REMEMBER

1. Both Γ and τ are dimensionless and may be complex.
2. $1+\Gamma=\tau$
3. $0\le|\Gamma|\le1$
4. Since $|\Gamma|<1$, standing wave ratio (s) is always positive and greater than or equal to unity, i.e. $s\ge1$

7.12 NORMAL INCIDENCE OF UNIFORM PLANE WAVE ON A PERFECT CONDUCTOR

Consider that a uniform plane electromagnetic wave, propagating along $+\boldsymbol{a}_z$ direction in a perfect dielectric medium $(\sigma_1=0)$ of permeability μ and permittivity ε, is incident normally on the surface of a perfect flat conductor ($\sigma_2=\infty$). The conductor surface is taken at $z=0$ plane, as shown in Figure 7.4.

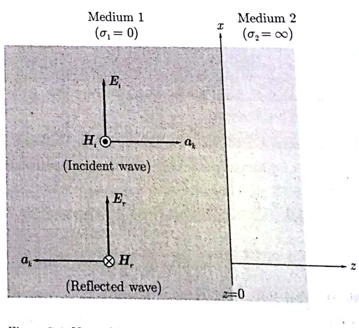

Figure 7.4: Normal Incidence of Uniform Plane Wave on a Perfect Conductor

Since the depth of penetration for a perfect conductor is zero, the wave will not travel beyond the $z=0$ plane. In general, the field components of incident and reflected waves for the interface are expressed as given in table below.

Table 7.2: Representation of Field Components of Incident and Transmitted Wave for Interface between Dielectric and Perfect Conductor

	Electric field Components	Magnetic field components
Incident wave	$\boldsymbol{E}_{is}(z)=E_{i0}e^{-j\beta_1 z}\boldsymbol{a}_x$	$\boldsymbol{H}_{is}(z)=H_{i0}e^{-j\beta_1 z}\boldsymbol{a}_y=\frac{E_{i0}}{\eta_1}e^{-j\beta_1 z}\boldsymbol{a}_y$
Reflected wave	$\boldsymbol{E}_{rs}(z)=E_{r0}e^{j\beta_1 z}\boldsymbol{a}_x$	$\boldsymbol{H}_{rs}(z)=H_{r0}e^{j\beta_1 z}(-\boldsymbol{a}_y)=-\frac{E_{r0}}{\eta_1}e^{j\beta_1 z}\boldsymbol{a}_y$

7.12.1 Reflection and Transmission Coefficients

Notice from Figure 7.4 that the wave is totally reflected. So, the reflection coefficient is given by

$$\Gamma=\frac{E_{ro}}{E_{io}}=-1$$

Since, there is no transmitted wave (i.e. $E_{t0}=0$). So, the transmission coefficient is zero. i.e.

$$\tau=0$$

7.12.2 Standing Wave Ratio

Since, the wave is totally reflected in this case with reflection coefficient $|\Gamma|=1$. So, the standing wave ratio is infinite. i.e.

$$s=\infty$$

7.13 OBLIQUE INCIDENCE OF UNIFORM PLANE WAVE AT THE INTERFACE BETWEEN TWO DIELECTRICS

For oblique incidence of uniform plane wave at the interface between two dielectrics, we consider the following two cases:

1. Parallel Polarization
2. Perpendicular polarization

7.13.1 Parallel Polarization

Figure 7.5 shows the oblique incidence of a uniform plane wave (parallel polarized) where the $\boldsymbol{E}$ field lies in the xz-plane, the plane of incidence. Both the mediums are lossless.

Reflection and Transmission Coefficients for Parallel Polarization

The reflection and transmission coefficients for the parallel polarised wave are defined as

$$\Gamma_{\parallel}=\frac{E_{r0}}{E_{i0}}=\frac{\eta_2\cos\theta_t-\eta_1\cos\theta_i}{\eta_2\cos\theta_t+\eta_1\cos\theta_i}$$

and
$$\tau_{\parallel}=\frac{E_{t0}}{E_{i0}}=\frac{2\eta_2\cos\theta_i}{\eta_2\cos\theta_t+\eta_1\cos\theta_i}$$

Brewster Angle for Parallel Polarized Wave

The incident angle at which there is no reflection (i.e. $E_{r0}=0$) is called Brewster angle. For the parallel polarized wave propagating through lossless mediums, the Brewster angle $\theta_{B\parallel}$ is expressed as

$$\sin^2\theta_{B\parallel}=\frac{1-\mu_2\varepsilon_1/\mu_1\varepsilon_2}{1-(\varepsilon_1/\varepsilon_2)^2}$$

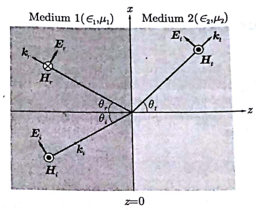

Figure 7.5: Oblique Incidence of Parallel Polarized Wave at the Interface between Two Lossless Dielectrics

7.13.2 Perpendicular Polarization

Consider the oblique incidence of a perpendicular polarized wave shown in Figure 7.6. Both the mediums are lossless and the $\boldsymbol{E}$ field is perpendicular to the xz-plane, the plane of incidence.

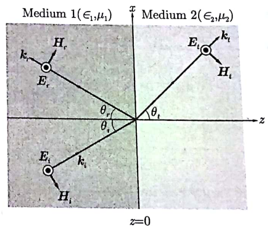

Figure 7.6: Oblique Incidence of Perpendicular Polarized Wave at the Interface between Two Lossless Dielectrics

Reflection and Transmission Coefficients for Perpendicular Polarization

The reflection and transmission coefficients for perpendicular polarized wave are given by

$$\Gamma_{\perp}=\frac{E_{r0}}{E_{i0}}=\frac{\eta_2\cos\theta_i-\eta_1\cos\theta_t}{\eta_2\cos\theta_i+\eta_1\cos\theta_t}$$

and
$$\tau_{\perp}=\frac{E_{t0}}{E_{i0}}=\frac{2\eta_2\cos\theta_i}{\eta_2\cos\theta_i+\eta_1\cos\theta_t}$$

Brewster Angle for Perpendicular Polarized Wave

For the perpendicular polarized wave propagating through lossless mediums, the Brewster angle, $\theta_{B_\perp}$ is expressed as

$$\sin^2\theta_{B_\perp} = \frac{1-\mu_1\varepsilon_2/\mu_2\varepsilon_1}{1-(\mu_1/\mu_2)^2}$$

7.14 OBLIQUE INCIDENCE OF UNIFORM PLANE WAVE ON A PERFECT CONDUCTOR

Consider that a uniform plane electromagnetic wave, propagating along $+\boldsymbol{a}_z$ direction in a perfect dielectric medium ($\sigma_1 = 0$) of permeability μ and permittivity ε, is incident obliquely on the surface of a perfect flat conductor. Again, we will consider the two cases: parallel polarization and perpendicular polarization.

7.14.1 Parallel Polarisation

Figure 7.7 shows the oblique incidence of a parallel polarised wave on a perfect conductor. Electric field of the incident and reflected waves lie in the xz-plane, the plane of incidence. As the depth of penetration for a perfect conductor is zero, the wave will not travel beyond the $z = 0$ plane. So, the reflection coefficient of parallel polarisation is obtained as

$$\Gamma_{\parallel} = \frac{E_{r0}}{E_{i0}} = -1$$

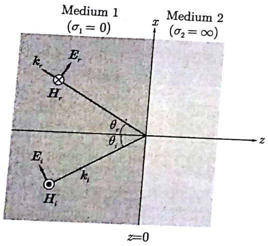

Figure 7.7: Oblique Incidence of Parallel Polarized Wave on the Perfect Conductor

7.14.2 Perpendicular Polarisation

In this case, the electric field is perpendicular to the plane of incidence. Consider a perpendicular polarised wave incident on a perfect conductor as shown in Figure 7.8.

Since, the depth of penetration for a perfect conductor is zero, the wave will not travel beyond the $z = 0$ plane. So, the reflection coefficient of perpendicular polarisation is obtained as

$$\Gamma_{\perp} = \frac{E_{r0}}{E_{i0}} = -1$$

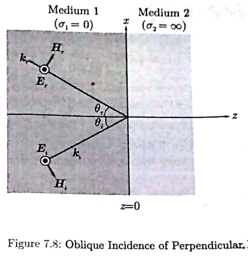

Figure 7.8: Oblique Incidence of Perpendicular Polarized Wave on the Perfect Conductor

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EXERCISE 7.1

MCQ 7.1.1 In a certain medium electric field intensity of a propagating wave is given by

$$\boldsymbol{E}(x,t) = E_0 e^{-\alpha x}\sin(\omega t - \beta x)\boldsymbol{a}_y \text{ V/m}$$

The electric field phasor of the wave will be

(A) $E_0 e^{-(\alpha+j\beta)x}\boldsymbol{a}_y$ V/m

(B) $jE_0 e^{-(\alpha+j\beta)x}\boldsymbol{a}_y$ V/m

(C) $-jE_0 e^{-(\alpha+j\beta)x}\boldsymbol{a}_y$ V/m

(D) $-jE_0 e^{(\alpha-j\beta x)}\boldsymbol{a}_y$ V/m

MCQ 7.1.2 **Assertion (A) :** $\boldsymbol{E} = E_0\sin(z)\cos(ct)\boldsymbol{a}_x$ represents the electric field of a plane wave in free space.

Reason (R) : A plane wave f propagating with velocity v_p in $+\boldsymbol{a}_z$ direction must satisfy the equation

$$\frac{\partial^2 f}{\partial t^2} - v_p^2\frac{\partial^2 f}{\partial z^2} = 0$$

(A) Both A and R are true and R is the correct explanation of A.

(B) Both A and R are true but R is not the correct explanation of A.

(C) A is true but R is false

(D) A is false but R is true

MCQ 7.1.3 A propagating wave in free space has magnetic field intensity

$$\boldsymbol{H} = 0.1\cos(10^9 t - \beta y)\boldsymbol{a}_z \text{ A/m}$$

What will be the electric field intensity of the wave at $y = 1$ cm at time, $t = 0.1$ ns ?

(A) $-37.7\boldsymbol{a}_x$ V/m

(B) $-37.6\boldsymbol{a}_x$ V/m

(C) $-19.8\boldsymbol{a}_x$ V/m

(D) $37.6\boldsymbol{a}_x$ V/m

MCQ 7.1.4 Electric field intensity of linearly polarized plane wave in free space is given by $\boldsymbol{E} = (5\boldsymbol{a}_y - 6\boldsymbol{a}_z)\cos(\omega t - 50z)$ V/m. The phasor form of magnetic field intensity of the wave will be

(A) $-\eta_0(5\boldsymbol{a}_x + 6\boldsymbol{a}_y)e^{-j50z}$ V/m

(B) $(5\boldsymbol{a}_x - 6\boldsymbol{a}_z)\frac{e^{-j50z}}{\eta_0}$ V/m

(C) $(5\boldsymbol{a}_x - 6\boldsymbol{a}_y)\frac{e^{-j50z}}{\eta_0}$ V/m

(D) $-(5\boldsymbol{a}_x + 6\boldsymbol{a}_y)\frac{e^{-j50z}}{\eta_0}$ V/m

MCQ 7.1.5 In a perfect conductor (resistivity, $\rho \approx 0$) magnetic field of any EM wave

(A) lags electric field by 90°

(B) leads electric field by 45°

(C) lags electric field by 45°

(D) will be in phase with electric field

Common Data For Q. 6 and 7 :

An electromagnetic wave travels in free space with the electric field component

$$\boldsymbol{E}_s = (5\boldsymbol{a}_x + 10\boldsymbol{a}_z)e^{-j(4x-2z)} \text{ V/m}$$

MCQ 7.1.6 What will be the phasor form of magnetic field intensity of the wave ?

(A) $-29.66e^{-j(4x-2z)}$ mA/m

(B) $-5\sqrt{5}\,e^{-j(4x-2z)}$ mA/m

(C) $29.66e^{-j(4x-2z)}$ mA/m

(D) $-29.66e^{-j(4x-2z)}$ A/m

MCQ 7.1.7 What will be the time average power density of the electromagnetic wave ?

(A) $(665.9\boldsymbol{a}_x - 331.6\boldsymbol{a}_z)$ W/m^2

(B) $(148.9\boldsymbol{a}_x - 74.15\boldsymbol{a}_z)$ W/m^2

(C) $(-331.6\boldsymbol{a}_x + 665.9\boldsymbol{a}_z)$ W/m^2

(D) $(-74.15\boldsymbol{a}_x + 148.9\boldsymbol{a}_z)$ W/m^2

MCQ 7.1.8 A propagating wave has the phasor form of its electric field intensity defined as $\boldsymbol{E}_s = (-2\sqrt{3}\,\boldsymbol{a}_x + \sqrt{3}\,\boldsymbol{a}_y - \boldsymbol{a}_z)e^{-j0.1\pi(-3x+\sqrt{3}y-2z)}$ V/m. The wave is linearly polarized along the direction of

(A) $-3\boldsymbol{a}_x + \sqrt{3}\,\boldsymbol{a}_y - 2\boldsymbol{a}_z$

(B) $-2\sqrt{3}\,\boldsymbol{a}_x + \sqrt{3}\,\boldsymbol{a}_y - \boldsymbol{a}_z$

(C) $3\boldsymbol{a}_x - \sqrt{3}\,\boldsymbol{a}_y + 2\boldsymbol{a}_z$

(D) $2\sqrt{3}\,\boldsymbol{a}_x - \sqrt{3}\,\boldsymbol{a}_y + \boldsymbol{a}_z$

Common Data For Q. 9 and 10 :

In free space an electric field intensity vector is given by

$$\boldsymbol{E} = 100\cos(\omega t - \beta z)\boldsymbol{a}_x$$

where ω and β are constants.

MCQ 7.1.9 If $\beta = \frac{\omega}{\sqrt{\mu_0\varepsilon_0}}$. what will be the magnetic flux density vector $\boldsymbol{B}$?

$$\left(\frac{1}{\sqrt{\mu_0\varepsilon_0}} = 3 \times 10^{+8} \text{ m/s}\right)$$

(A) $3 \times 10^{10}\cos(\omega t - \beta z)\boldsymbol{a}_y$

(B) $3.33 \times 10^{-7}\cos(\omega t - \beta z)\boldsymbol{a}_y$

(C) $3 \times 10^{8}\cos(\omega t - \beta z)\boldsymbol{a}_y$

(D) $3.33 \times 10^{-6}\cos(\omega t - \beta z)\boldsymbol{a}_y$

MCQ 7.1.10 The poynting vector of the E-M field will be

(A) $10^4\sqrt{\frac{\varepsilon_0}{\mu_0}}\cos^2(\omega t - \beta z)\boldsymbol{a}_z$

(B) $10^4\sqrt{\frac{\mu_0}{\varepsilon_0}}\cos^2(\omega t - \beta z)\boldsymbol{a}_z$

(C) $10^4\sqrt{\mu_0}\cos^2(\omega t - \beta z)\boldsymbol{a}_z$

(D) $\frac{10^4}{\sqrt{\mu_0}}\cos^2(\omega t - \beta z)\boldsymbol{a}_z$

MCQ 7.1.11 The electric field associated with a sinusoidally time varying electromagnetic field is given by $\boldsymbol{E} = 5\sin\pi x\sin(2\pi \times 10^8 - \sqrt{3}\,\pi z)\boldsymbol{a}_y$ V/m

The time average stored energy density in the electric field is

(A) $\frac{4}{25}\varepsilon_0\sin^2\pi x$

(B) $\frac{25\varepsilon_0}{4}\sin^2\pi x$

(C) $\frac{5\varepsilon_0}{4}\sin 2\pi x$

(D) $\frac{25\varepsilon_0}{4}\sin 2\pi x$

MCQ 7.1.12 Electric field associated with a sinusoidally time varying electromagnetic field is given by $\boldsymbol{E} = 10\sin(\pi y)\sin(6\pi \times 10^8 t - \sqrt{3}\pi x)\boldsymbol{a}_z$ V/m. What will be the time average stored energy density in the magnetic field ?

(A) $\frac{10^{-9}}{\pi}(25 + 50\sin^2\pi x)$

(B) $\frac{10^{-9}}{144\pi}(25 + 50\sin^2\pi x)$

(C) $\frac{144 \times 10^9}{\pi}(25 + 50\sin^2\pi x)$

(D) $\frac{\pi}{144}(25 + 50\sin^2\pi x)$

MCQ 7.1.13 An electromagnetic wave propagating in free space is incident on the surface of a dielectric medium $(\mu_0, 4\varepsilon_0)$. If the magnitude of the electric field of incident wave is E_0 then what will be the magnitude of the electric field of the reflected wave ?

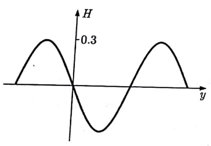
(A) $-2E_0/3$ (B) $-E_0/3$

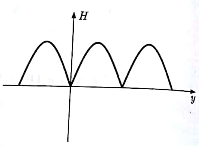
(C) $E_0/2$ (D) $-E_0$

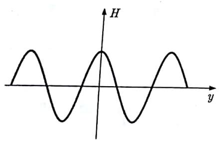
MCQ 7.1.14 Magnetic field intensity of a propagating wave in free space is given by

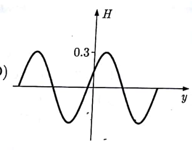
$$\boldsymbol{H} = 0.3\cos(\omega t - \beta y)\boldsymbol{a}_z \text{ A/m}$$

If the total time period of the wave be T then the plot of H versus y at time, $t = \frac{T}{8}$ will be

(A)


(B)


(C)


(D)


MCQ 7.1.15 A uniform plane wave is propagating with a velocity of 7.5×10^7 m/s in a lossless medium having relative permeability $\mu_r = 4.8$. The electric field phasor of the wave is given by

$$\boldsymbol{E}_s = 5e^{j0.3x}\boldsymbol{a}_z \text{ V/m}$$

What will be the magnetic field intensity of the wave ?

(A) $11.05\cos(9.54 \times 10^6 t + 0.3x)\boldsymbol{a}_y$ mA/m

(B) $22.13\cos(9.54 \times 10^6 t + 0.3x)\boldsymbol{a}_y$ mA/m

(C) $22.13\cos(9.54 \times 10^6 t + 0.3z)\boldsymbol{a}_y$ mA/m

(D) $11.05\cos(2.25 \times 10^7 t + 0.3x)\boldsymbol{a}_y$ mA/m

MCQ 7.1.16 A uniform plane wave is propagating at a velocity of 7×10^7 m/s in a perfect dielectric such that the electric and magnetic fields of the wave are given by

$$\boldsymbol{E}(x,t) = 900\cos(5 \times 10^6\pi t - \beta x)\boldsymbol{a}_y \text{ V/m}$$
$$\boldsymbol{H}(x,t) = 1.9\cos(5 \times 10^6\pi t - \beta x)\boldsymbol{a}_z \text{ V/m}$$

The relative permittivity and relative permeability of the medium will be respectively

(A) 1.70, 2.69 (B) 3.4, 5.37

(C) 1.70, 1.58 (D) 2.37, 2.69

MCQ 7.1.17 An electromagnetic wave is propagating in free space in $-\boldsymbol{a}_z$ direction with a frequency ω and phase angle zero. The EM wave is polarized in $+\boldsymbol{a}_z$ direction. If the amplitude of electric field of the wave is E_0 then the magnetic field of the wave will be

(A) $\frac{E_0}{\eta_0}\cos\left(\omega t + \frac{\omega}{c}x\right)\boldsymbol{a}_y$ (B) $\eta_0 E_0\cos(\omega t + \omega c x)\boldsymbol{a}_y$

(C) $-\frac{E_0}{\eta_0}\cos\left(\omega t + \frac{\omega}{c}x\right)\boldsymbol{a}_y$ (D) $\frac{E_0}{\eta_0}\cos\left(\omega t - \frac{\omega}{c}x\right)\boldsymbol{a}_y$

MCQ 7.1.18 What will be the electric field of a plane wave polarized parallel to the x-z plane and propagating in free space in the direction from origin to the point (1,1,1), that has the amplitude E_0 and frequency ω with zero phase angle ?

(A) $E_0\cos\left[\omega t - \frac{\omega}{\sqrt{3}\,c}(x+y+z)\right]\left(\frac{\boldsymbol{a}_x - \boldsymbol{a}_z}{\sqrt{2}}\right)$

(B) $E_0\cos\left[\omega t + \frac{\omega}{\sqrt{3}\,c}(x+y+z)\right]\left(\frac{\boldsymbol{a}_x - \boldsymbol{a}_z}{\sqrt{2}}\right)$

(C) $E_0\cos\left[\omega t - \frac{\omega}{c}(x+y+z)\right]\left(\frac{\boldsymbol{a}_x + \boldsymbol{a}_z}{\sqrt{2}}\right)$

(D) $E_0\cos\left[\omega t + \frac{\omega}{c}(x+y+z)\right]\left(\frac{\boldsymbol{a}_x + \boldsymbol{a}_z}{\sqrt{2}}\right)$

MCQ 7.1.19 With a thickness t, silver coating is done for a microwave experiment to operate at a frequency of 10 GHz. For the successful experiment t should be (for silver, $\mu_r = \varepsilon_r \approx 1$, $\sigma = 6.25 \times 10^7$ S/m)

(A) greater than 0.64 μm (B) less than 0.64 μm

(C) exactly equal to 0.64 μm (D) none of these

MCQ 7.1.20 In a nonmagnetic material of conductivity $\sigma = 2 \times 10^7$ S/m, electric field of a propagating plane wave is given by

$$\boldsymbol{E} = 3\cos(10^7 t - 0.2y)\boldsymbol{a}_x + 2\sin(10^7 t - 0.2y)\boldsymbol{a}_z \text{ V/m}$$

What will be the value of complex permittivity of the medium ?

(A) $(2 - j36\varepsilon_0)$ F/m

(B) $(36\varepsilon_0 - j2)$ F/m

(C) $(36 - j2)$ F/m

(D) $(36\varepsilon_0 + j2)$ F/m

MCQ 7.1.21 **Assertion (A) :** All the metals are opaque.

Reason (R) : Skin depth of metals are in the range of nanometers.

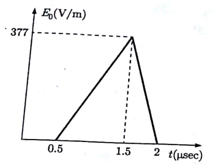
(A) Both A and R are true and R is the correct explanation of A.

(B) Both A and R are true but R is not the correct explanation of A.

(C) A is true but R is false.

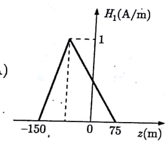
(D) A is false but R is true.

MCQ 7.1.22 In the plane $z = 0$, electric field of a wave propagating in $+\boldsymbol{a}_z$ direction in free space is $\boldsymbol{E}_0$ which is varying with time t as shown in the figure.

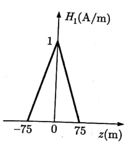


If the magnetic field intensity of the wave at $t = 1\,\mu$sec be $\boldsymbol{H}_1$ then the plot of H_1 versus z will be

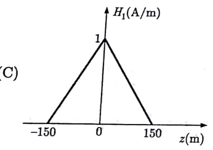
(A)



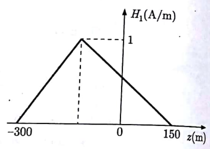
(B)



(C)



(D)



MCQ 7.1.23 Electric field of an electromagnetic wave propagating in a medium in $+\boldsymbol{a}_x$ direction is given by $\boldsymbol{E}_s = E_0(\boldsymbol{a}_y - j\boldsymbol{a}_z)e^{-j\beta x}$. The wave is

(A) left hand circularly polarized

(B) Right hand circularly polarized

(C) elliptically polarized

(D) linearly polarized

MCQ 7.1.24 An electromagnetic wave has the electric field intensity in the phasor form given by $\boldsymbol{E}_s = 4(\boldsymbol{a}_z - j\boldsymbol{a}_x)e^{-j\beta y}$. The EM wave is incident on a perfect conductor located at $y = 0$. What will be the polarization of the reflected wave ?

(A) left hand circular

(B) Right hand circular

(C) elliptical

(D) linear

MCQ 7.1.25 An electromagnetic wave propagating in free space is incident on a perfectly conducting slab placed at $x \geq 0$. The electric field of the incident wave in the phasor form is given by $\boldsymbol{E}_{is} = 10\boldsymbol{a}_z e^{-j(6y+8x)}$ V/m. The net electric field of the total wave (incident and reflected both) in free space after reflection will be

(A) $10\boldsymbol{a}_z e^{-j(6y-8x)}$ V/m

(B) $-10\boldsymbol{a}_z e^{-j(6y-8x)}$ V/m

(C) $-j20\boldsymbol{a}_z e^{-j6y}\sin 8x$ V/m

(D) $j20\boldsymbol{a}_z e^{-j6y}\sin 8x$ V/m

MCQ 7.1.26 Electric field intensity of an EM wave propagating in free space is given by

$$\boldsymbol{E}_{is} = 25\boldsymbol{a}_x e^{-j(6z+8y)}\ \text{V/m}$$

If the wave is incident on a perfectly conducting plane at $y = 0$ then the magnetic field intensity of the reflected wave will be

(A) $-\left(\frac{\boldsymbol{a}_y}{8\pi} + \frac{\boldsymbol{a}_z}{6\pi}\right)e^{-j(6z-8y)}$ A/m

(B) $\left(\frac{\boldsymbol{a}_y}{8\pi} + \frac{\boldsymbol{a}_z}{6\pi}\right)e^{-j(6z-8y)}$ A/m

(C) $\left(\frac{\boldsymbol{a}_y}{8\pi} + \frac{\boldsymbol{a}_z}{6\pi}\right)e^{j(6z-8y)}$

(D) $-\left(\frac{\boldsymbol{a}_y}{8\pi} + \frac{\boldsymbol{a}_z}{6\pi}\right)e^{j(6z-8y)}$ A/m

MCQ 7.1.27 The complex electric field vector of a uniform plane wave propagating in free space is given by $\boldsymbol{E}_s = (\sqrt{3}\,\boldsymbol{a}_x - \boldsymbol{a}_y - 2\sqrt{3}\,\boldsymbol{a}_z)e^{-j0.01\pi(-3x+\sqrt{3}y-2z)}$ V/m. The unit vector in the direction of propagation of the wave will be

(A) $\dfrac{-3\boldsymbol{a}_x + \sqrt{3}\,\boldsymbol{a}_y - 2\boldsymbol{a}_z}{16}$

(B) $\dfrac{-3\boldsymbol{a}_x + \sqrt{3}\,\boldsymbol{a}_y - 2\boldsymbol{a}_z}{4}$

(C) $-4(3\boldsymbol{a}_x - \sqrt{3}\,\boldsymbol{a}_y + 2\boldsymbol{a}_z)$

(D) $-\dfrac{(3\boldsymbol{a}_x + \sqrt{3}\,\boldsymbol{a}_y - 2\boldsymbol{a}_z)}{4}$

Common Data For Q. 28 and 29 :

In free space complex electric field vector of a uniform plane wave is given by

$$\boldsymbol{E}_s = (\sqrt{3}\,\boldsymbol{a}_x + \boldsymbol{a}_z)e^{-j\frac{\pi}{25}(\sqrt{3}x-2y-3z)}\ \text{V/m}$$

MCQ 7.1.28 The apparent wavelengths along the x, y and z axes are

	λ_x	λ_y	λ_z
(A)	16.7 m	25 m	28.87 m
(B)	28.87 m	16.7 m	25 m
(C)	16.7 m	28.87 m	25 m
(D)	28.87 m	25 m	16.7 m

MCQ 7.1.29 The apparent phase velocities along the x, y and z axes are

	v_{Px}	v_{Py}	v_{Pz}
(A)	1.73×10^{10} m/s	1.5×10^{10} m/s	1×10^{10} m/s
(B)	6.93×10^{8} m/s	6×10^{8} m/s	4×10^{8} m/s
(C)	2.77×10^{7} m/s	2.4×10^{7} m/s	1.6×10^{7} m/s
(D)	1.2×10^{9} m/s	1.2×10^{9} m/s	1.2×10^{9} m/s

MCQ 7.1.30 Which of the following complex vector field represents the electric field of a uniform plane wave ?

(A) $\left(-j\boldsymbol{a}_x - 2\boldsymbol{a}_y - j\sqrt{3}\,\boldsymbol{a}_z\right)e^{-j0.6\pi(\sqrt{3}y+z)}$

(B) $\left(\boldsymbol{a}_x - j2\boldsymbol{a}_y - \sqrt{3}\,\boldsymbol{a}_z\right)e^{-j0.05\pi(x+\sqrt{3}z)}$

(C) $\left[\left(\sqrt{3} + j\frac{1}{2}\right)\boldsymbol{a}_x + \left(1 + \frac{j\sqrt{3}}{2}\right)\boldsymbol{a}_y - j\sqrt{3}\,\boldsymbol{a}_z\right]e^{-j0.02\pi(\sqrt{3}x+3y+2z)}$

(D) $\left[\left(-\sqrt{3} - j\frac{1}{2}\right)\boldsymbol{a}_x + \left(1 - j\frac{\sqrt{3}}{2}\right)\boldsymbol{a}_y + j\sqrt{3}\,\boldsymbol{a}_z\right]e^{-j0.02\pi(\sqrt{3}x+3y+2z)}$

MCQ 7.1.31 Which of the following pairs of vector $\boldsymbol{E}_s$ and $\boldsymbol{H}_s$ field represents the complex electric and magnetic field vectors of a uniform plane wave ?

	$\boldsymbol{E}_s$	$\boldsymbol{H}_s$
(A)	$\left(j\boldsymbol{a}_x + 2\boldsymbol{a}_y + j\sqrt{3}\,\boldsymbol{a}_z\right)e^{-j\pi(\sqrt{3}x+z)}$ V/m	$\left(\boldsymbol{a}_x - j2\boldsymbol{a}_y - \sqrt{3}\,\boldsymbol{a}_z\right)e^{-j\pi(\sqrt{3}x+z)}$ A/m
(B)	$\left(j\boldsymbol{a}_x + j\sqrt{3}\,\boldsymbol{a}_z\right)e^{-j\pi(x+\sqrt{3}z)}$ V/m	$\left(-j\boldsymbol{a}_x + j\sqrt{3}\,\boldsymbol{a}_z\right)e^{-j\pi(x+\sqrt{3}z)}$ A/m
(C)	$\left(j\boldsymbol{a}_x - j\sqrt{3}\,\boldsymbol{a}_z\right)e^{-j\pi(x+\sqrt{3}z)}$ V/m	$\left(-\sqrt{3}\,j\boldsymbol{a}_x - j\boldsymbol{a}_z\right)e^{-j\pi(x+\sqrt{3}z)}$ A/m
(D)	$\left(-j\boldsymbol{a}_x - 2\boldsymbol{a}_y + j\sqrt{3}\,\boldsymbol{a}_z\right)e^{-j0.1\pi(\sqrt{3}x+z)}$ V/m	$\left(\boldsymbol{a}_x - j2\boldsymbol{a}_y - \sqrt{3}\,\boldsymbol{a}_z\right)e^{-j0.1\pi(\sqrt{3}x+z)}$ A/m

MCQ 7.1.32 The following fields exist in charge free regions

$$\boldsymbol{P} = 60\sin(\omega t + 10x)\,\boldsymbol{a}_z$$
$$\boldsymbol{Q} = \frac{10}{\rho}\cos(\omega t - 2\rho)\,\boldsymbol{a}_\phi$$
$$\boldsymbol{R} = 3\rho^2\cot\phi\,\boldsymbol{a}_\rho + \frac{1}{\rho}\cos\phi\,\boldsymbol{a}_\phi$$
$$\boldsymbol{S} = \frac{1}{r}\sin\theta\sin(\omega t - 6r)\,\boldsymbol{a}_\theta$$

The possible electromagnetic fields are

(A) $\boldsymbol{P}, \boldsymbol{Q}$
(B) $\boldsymbol{R}, \boldsymbol{S}$
(C) $\boldsymbol{P}, \boldsymbol{R}$
(D) $\boldsymbol{Q}, \boldsymbol{S}$

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EXERCISE 7.2

QUES 7.2.1 In air, magnetic field intensity is given by $\boldsymbol{H} = 10\cos(6\times10^7 t - ky)\,\boldsymbol{a}_z$ A/m . Wave number k for the EM wave will be ____ rad/m.

QUES 7.2.2 An electromagnetic wave is propagating in certain non magnetic material such that the magnetic field intensity at any point is given by

$$\boldsymbol{H} = 1.5\cos(10^9 t - 5z)\,\boldsymbol{a}_x \text{ A/m}$$

The phase velocity of the wave in the medium will be ____ $\times 10^8$ m/s.

QUES 7.2.3 Magnetic field intensity in a certain non-magnetic medium is given by

$$\boldsymbol{H} = H_0\cos(\omega t - \beta y)\,\boldsymbol{a}_z \text{ A/m}$$

If the wavelength of the EM wave in the medium be 12.6 m then what will be the phase constant β (in rad/m) in that medium ?

QUES 7.2.4 In a nonmagnetic material electric field intensity is given by

$$\boldsymbol{E} = 8\cos(4\times10^8 t - 2x)\,\boldsymbol{a}_y \text{ V/m}$$

What is the relative permittivity of the medium ?

QUES 7.2.5 Electric field intensity in free space is $\boldsymbol{E} = 12\cos(5\times10^8 t - \beta z)\,\boldsymbol{a}_x$ V/m. The time period of the wave will be ____ ns.

QUES 7.2.6 In air, a propagating wave has electric field intensity given by

$$\boldsymbol{E} = 9\cos(4\times10^8 t - \beta x)\,\boldsymbol{a}_z \text{ V/m}$$

What will be the time taken (in ns) by the wave to travel one-fourth of it's total wave ?

QUES 7.2.7 What will be the intrinsic impedance (in Ω) of a lossless, nonmagnetic dielectric material having relative permittivity $\varepsilon_r = 2.25$?

QUES 7.2.8 A radio wave is propagating at a frequency of 0.5 MHz in a medium ($\sigma = 3\times10^7$ S/m, $\mu_r = \varepsilon_r \approx 1$).The wave length of the radio wave in that medium will be ____ mm.

QUES 7.2.9 Phasor form of magnetic field intensity of a uniform plane wave in free space is given as $\boldsymbol{H}_s = (2 + j5)(4\boldsymbol{a}_y + 2j\boldsymbol{a}_z)e^{-j\beta x}$ A/m. What is the maximum electric field (in kV/m) of the plane wave ?

QUES 7.2.10 An electromagnetic wave is propagating from free space to a certain medium having relative permittivity $\varepsilon_r = 9$. If wavelength of the wave in the medium be 20 cm then what would be it's wavelength (in cm) in free space ?

QUES 7.2.11 If some free charge is being embedded in a piece of glass, then the charge will flow out to the surface nearly after _____ second.
(For glass relative permittivity $\varepsilon_r = 2.25$, conductivity $\sigma = 10^{-12}\,\text{S/m}$)

QUES 7.2.12 In a certain medium ($\varepsilon_r = 4$, $\mu_r = 4$). A plane wave is propagating such that the electric field intensity of the wave is $\boldsymbol{E} = E_0 e^{-x/3}\sin(10^8 t - \beta x)\boldsymbol{a}_y$ V/m. The loss tangent of the medium will be ____

Common Data For Q. 13 and 14:

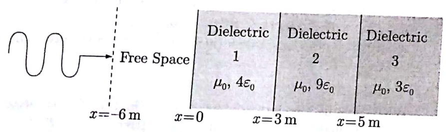
In a lossy medium ($\varepsilon_r = 8$, $\mu_r = 0.5$, $\sigma = 0.01\,\text{S/m}$ a plane wave is travelling in $+\boldsymbol{a}_z$ direction that has the electric field intensity $\boldsymbol{E} = 0.5\cos(10^9\pi t + \pi/3)\boldsymbol{a}_x$ at $z = 0$.

QUES 7.2.13 What will be the distance traveled by the wave to have a phase shift of $10°$?

• **QUES 7.2.14** After traveling a distance z, the amplitude of the wave is reduced by 40%. So, the value of z equals to ____ mm.

QUES 7.2.15 A plane wave is propagating with frequency $f = 50$ kHz in a medium ($\sigma = 2\,\text{S/m}$, $\varepsilon_r = 80$, $\mu_r = 4$). What will be the skin depth (in meter) of the medium ?

QUES 7.2.16 Three different dielectrics of permittivities $4\varepsilon_0$, $9\varepsilon_0$ and $3\varepsilon_0$ are defined in the space as shown in figure. If the leading edge of a uniform plane wave propagating in $\boldsymbol{a}_x$ direction is incident on the plane $x = -6$ m then how much time (in μs) it will take to strike the interface defined by the dielectric 2 and dielectric 3 ?



Common Data For Q. 17 and 18 :

An electromagnetic wave of 50 MHz frequency is incident on a dielectric medium such that it's skin depth is 0.32 mm.
(~~Permittivity~~ of dielectric $= 6.28 \times 10^{-7}$)
Permeability .

QUES 7.2.17 The conductivity of the dielectric will be ____ $\times 10^5$ S/m.

QUES 7.2.18 If an electromagnetic wave of 8 GHz frequency travels a distance of 0.175 mm in the dielectric medium then it's field intensity will be reduced by ___ dB.

QUES 7.2.19 An electromagnetic wave propagating in free space has magnetic field intensity $\boldsymbol{H} = 0.1\cos(\omega t - \beta y)\boldsymbol{a}_x$ A/m. What will be the total power (in mW) passing through a square plate of side 20 cm located in the plane $x + y = 2$?

• **QUES 7.2.20** An electromagnetic wave propagating in a lossless medium ($\mu_1 = 4\mu_0$, $\varepsilon_1 = \varepsilon_0$, $\sigma_1 = 0$) defined in the region $y > 0$ is incident on a lossy medium ($\mu_2 = \mu_0$, $\varepsilon_2 = 4\varepsilon_0$, $\sigma_2 = 0.1\,\text{S/m}$) defined in the region $y \le 0$. The electric field intensity of the incident wave in lossless medium is given by

$$\boldsymbol{E}_{is} = 5e^{-j\beta y}\boldsymbol{a}_z\ \text{V/m}$$

What will be the standing wave ratio ?

QUES 7.2.21 Phasor form of electric field intensity of a uniform plane wave is given by

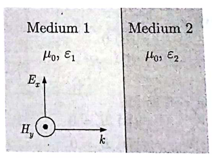
$$\boldsymbol{E}_s = \left(\sqrt{3}\,\boldsymbol{a}_x - \frac{2}{\sqrt{3}}\boldsymbol{a}_y\right)e^{-j0.04\pi(-2x-3y+\sqrt{3}z)}\ \text{V/m}$$

The wavelength along the direction of propagation is ____ meter.

QUES 7.2.22 In free space the complex magnetic field vector of a uniform plane wave is given by $\boldsymbol{H}_s = -(\sqrt{3}\,\boldsymbol{a}_x + \boldsymbol{a}_z)e^{-j0.04\pi(\sqrt{3}x-2y-3z)}$ A/m. Frequency of the plane wave will be ____ MHz.

• **QUES 7.2.23** A uniform plane wave in region 1 is normally incident on the planner boundary separating regions 1 and 2. Both region are lossless and $\varepsilon_{r1} = \mu_{r1}^3$, $\varepsilon_{r2} = \mu_{r2}^3$. If the 20% of the energy in the incident wave is reflected at the boundary, the ratio $\varepsilon_{r2}/\varepsilon_{r1}$ is ____

QUES 7.2.24 An electromagnetic wave propagating in medium 1 (μ_0, ε_1) is incident on medium 2 (μ_0, ε_2) as shown in figure such that the electric field of reflected wave is 1/5 times of the electric field of incident wave. The value of $\varepsilon_1/\varepsilon_2$ equals to ____



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EXERCISE 7.3

MCQ 7.3.1 What will be the direction of wave propagation in a non magnetic medium in which magnetic field intensity at any point is given by

$$H = 3\cos(\omega t - kz)\boldsymbol{a}_x \text{ A/m}$$

(A) $+\boldsymbol{a}_z$ direction
(B) $-\boldsymbol{a}_z$ direction
(C) $+\boldsymbol{a}_x$ direction
(D) $+\boldsymbol{a}_y$ direction

MCQ 7.3.2 The skin depth in a poor conductor is independent of
(A) Permittivity
(B) Permeability
(C) Frequency
(D) None of these

MCQ 7.3.3 Poynting vector is given by
(A) $\boldsymbol{E} \times \boldsymbol{H}$ (B) $\boldsymbol{E} \cdot \boldsymbol{H}$
(C) $\boldsymbol{H} \times \boldsymbol{E}$ (D) $\boldsymbol{H} \cdot \boldsymbol{E}$

MCQ 7.3.4 Poynting vector gives
(A) rate of energy flow
(B) direction of polarisation
(C) electric field
(D) magnetic field

MCQ 7.3.5 $\boldsymbol{E} \cdot \boldsymbol{H}$ of a uniform plane wave is
(A) EH (B) 0
(C) ηE^2 (D) ηH^2

MCQ 7.3.6 For a uniform plane wave in the x-direction
(A) $E_x = 0$ (B) $H_x = 0$
(C) $E_x = 0$ and $H_x = 0$ (D) $E_z = 0$

MCQ 7.3.7 Depth of penetration in free space is
(A) infinity (B) $1/\alpha$
(C) 0 (D) small

MCQ 7.3.8 Complex Poynting vector, $\boldsymbol{P}$ is
(A) $P = E \times H^*$
(B) $\boldsymbol{P} = \boldsymbol{E} \times \boldsymbol{H}^*$
(C) $P = \frac{1}{2}\boldsymbol{E} \times \boldsymbol{H}^*$
(D) $\boldsymbol{E} \times \boldsymbol{H}$

MCQ 7.3.9 Uniform plane wave is
(A) longitudinal in nature
(B) transverse in nature
(C) neither transverse nor longitudinal
(D) x-directed

MCQ 7.3.10 The direction of propagation of EM wave to obtained from
(A) $\boldsymbol{E} \times \boldsymbol{H}$ (B) $\boldsymbol{E} \times \boldsymbol{H}$
(C) $\boldsymbol{E}$ (D) $\boldsymbol{H}$

MCQ 7.3.11 The velocity of an EM wave is
(A) inversely proportional to β
(B) inversely proportional to α
(C) directly proportional to β
(D) directly proportional to α

MCQ 7.3.12 Velocity of the wave in an ideal conductor is
(A) zero (B) very large
(C) moderate (D) small

MCQ 7.3.13 Velocity of an EM wave in free space is
(A) independent of f
(B) increases with increase in f
(C) decreases with increase in f
(D) zero

MCQ 7.3.14 The direction of propagation of an EM wave is given by
(A) the direction of $\boldsymbol{E}$
(B) the direction of $\boldsymbol{H}$
(C) the direction of $\boldsymbol{E} \times \boldsymbol{H}$
(D) the direction of $\boldsymbol{E} \cdot \boldsymbol{H}$

MCQ 7.3.15 For uniform plane wave propagating in z-direction
(A) $\boldsymbol{E}_z = 0$
(B) $\boldsymbol{H}_z = 0$
(C) $\boldsymbol{E}_y = 0$, $\boldsymbol{H}_y = 0$
(D) $\boldsymbol{E}_z = 0$, $\boldsymbol{H}_z = 0$

MCQ 7.3.16 Velocity of propagation of an EM wave is
(A) $\sqrt{\frac{\varepsilon_0}{\mu_0}}$ (B) $\frac{\mu_0}{\varepsilon_0}$
(C) $\frac{1}{\sqrt{\mu_0 \varepsilon_0}}$ (D) $\frac{\varepsilon_0}{\mu_0}$

MCQ 7.3.17 Consider the following statements regarding the complex Poynting vector $\mathcal{P}$ for the power radiated by a point source in an infinite homogeneous and lossless medium. Re($\mathcal{P}$) denotes the real part of $\mathcal{P}$, S denotes a spherical surface whose centre is at the point source, and $\boldsymbol{a}_n$ denotes the unit surface normal on S. Which of the following statements is TRUE?
(A) Re($\mathcal{P}$) remains constant at any radial distance from the source

(B) Re($\mathcal{P}$) increases with increasing radial distance from the source

(C) $\oiint_s \text{Re}(\mathcal{P}) \cdot (dS\boldsymbol{a}_n)$ remains constant at any radial distance from the source

(D) $\oiint_s \text{Re}(\mathcal{P}) \cdot (dS\boldsymbol{a}_n)$ decreases with increasing radial distance from the source

MCQ 7.3.18 The electric field of an electromagnetic wave propagation in the positive direction is given by $E = \boldsymbol{a}_x \sin(\omega t - \beta z) + \boldsymbol{a}_y \sin(\omega t - \beta z + \frac{\pi}{2})$. The wave is

(A) Linearly polarized in the z-direction

(B) Elliptically polarized

(C) Left-hand circularly polarized

(D) Right-hand circularly polarized

MCQ 7.3.19 If a plane electromagnetic wave satisfies the equation $\frac{\partial^2 E_x}{\partial z^2} = c^2 \frac{\partial^2 E_x}{\partial t^2}$, the wave propagates in the

(A) x-direction

(B) z-direction

(C) y-direction

(D) x-y plane at an angle of $45°$ between the x and z direction

MCQ 7.3.20 The intrinsic impedance of copper at high frequencies is

(A) purely resistive

(B) purely inductive

(C) complex with a capacitive component

(D) complex with an inductive component

MCQ 7.3.21 The depth of penetration of wave in a lossy dielectric increases with increasing

(A) conductivity (B) permeability

(C) wavelength (D) permittivity

MCQ 7.3.22 The polarization of wave with electric field vector $\boldsymbol{E} = E_0 e^{j(\omega t + \beta z)}(\boldsymbol{a}_x + \boldsymbol{a}_y)$ is

(A) linear (B) elliptical

(C) left hand circular (D) right hand circular

MCQ 7.3.23 Consider the following statements regarding depth of penetration or skin depth in a conductor :

1. It increases as frequency increases.
2. It is inversely proportional to square root of μ and σ.
3. It is inversely proportional to square root of f
4. It is directly proportional to square root of μ and σ.

Which of the above statements are correct ?

(A) 1 and 2 only (B) 3 and 4 only

(C) 2 and 3 only (D) 1, 2, 3 and 4

MCQ 7.3.24 Consider the following statements :

1. (Electric or magnetic) field must have two orthogonal linear components.
2. The two components must have the same magnitude.
3. The two components must have a time-phase difference of odd multiple of $90°$.

Which of these are the necessary and sufficient conditions for a time-harmonic wave to be circularly polarized at a given point in space ?

(A) 1 and 2 only (B) 2 and 3 only

(C) 1, 2 and 3 (D) 1 and 3 only

MCQ 7.3.25 **Assertion (A) :** The velocity of light in any medium is slower than that of vacuum.

Reason (R) : The dielectric constant of the vacuum is unity and is lesser than that of any other medium.

(A) Both A and R are individually true and R is the correct explanation of A

(B) Both A and R are individually true but R is not the correct explanation of A

(C) A is true but R is false

(D) A is false but R is true

MCQ 7.3.26 According to Poynting theorem, the vector product $\boldsymbol{E} \times \boldsymbol{H}$ is a measure of which one of the following?

(A) Stored energy density of the electric field

(B) Stored energy density of the magnetic

(C) Power dissipated per unit volume

(D) Rate of energy flow per unit area

MCQ 7.3.27 Poynting vector is a measure of which one of the following ?

(A) Maximum power flow through a surface surrounding the source

(B) Average power flow through the surface

(C) Instantaneous power flow through the surface

(D) Power dissipated by the surface

MCQ 7.3.28 The electric field component of a wave in free space is given by

$$E = 50\sin(10^7 t + kz)\,\boldsymbol{a}_y \text{ V/m}$$

Which one of the following is the correct inference that can be drawn from this expression ?

(A) The wave propagates along y-axis

(B) The wavelength is 188.5 m

(C) The wave number $k = 0.33$ rad/m

(D) The wave attenuates as it travels

MCQ 7.3.29 For an electromagnetic wave incident on a conducting medium, the depth of penetration

(A) is directly proportional to the attenuation constant

(B) is inversely proportional to the attenuation constant

(C) has a logarithmic relationship with the attenuation constant

(D) is independent of the attenuation constant

MCQ 7.3.30 What is the effect of the earth's magnetic field in the reflected wave at frequencies in the vicinity of gyro-frequency ?

(A) No attenuation in the reflected wave
(B) Decreased attenuation in the reflected wave
(C) Increased attenuation in the reflected wave
(D) Nominal attenuation in the reflected wave

MCQ 7.3.31 Consider the following statements :
For electromagnetic waves propagating in free space :
1. electrical field is perpendicular to direction of propagation
2. electrical field is along the direction of propagation
3. magnetic field is perpendicular to direction of propagation
4. magnetic field is along the direction of propagation

Which of these statements are correct ?
(A) 1 and 3 (B) 1 and 4
(C) 2 and 3 (D) 2 and 4

MCQ 7.3.32 Skin depth is the distance from the conductor surface where the field strength has fallen to
(A) π of its strength at the surface (B) e of its strength at the surface
(C) $(1/e)$ of its strength at the surface (D) $(1/\pi e)$ of its strength at the surface

MCQ 7.3.33 The depth of penetration of a wave in a lossy dielectric increases with increasing
(A) conductivity (B) permeability
(C) wavelength (D) permittivity

MCQ 7.3.34 When a plane wave propagates in a dielectric medium
(A) the average electric energy and the average magnetic energy densities are not equal.
(B) the average electric energy and the average magnetic energy densities are equal
(C) the net average energy density is finite
(D) the average electric energy density is not dependent on the average magnetic energy density

MCQ 7.3.35 What causes electromagnetic wave polarization ?
(A) Refraction
(B) Reflection
(C) Longitudinal nature of electromagnetic wave
(D) Transverse nature of electromagnetic wave

MCQ 7.3.36 Fields are said to be circularly polarized if their magnitudes are
(A) Equal and they are in phase
(B) Equal and they differ in phase by $\pm 90°$
(C) Unequal and they differ in phase by $\pm 90°$
(D) Unequal and they are in phase

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EXERCISE 7.4

MCQ 7.4.1 A plane wave propagating in air with $\boldsymbol{E} = (8\boldsymbol{a}_x + 6\boldsymbol{a}_y + 5\boldsymbol{a}_z)\, e^{j(\omega t + 3x - 4y)}$ V/m is incident on a perfectly conducting slab positioned at $x \le 0$. The $\boldsymbol{E}$ field of the reflected wave is
(A) $(-8\boldsymbol{a}_x - 6\boldsymbol{a}_y - 5\boldsymbol{a}_z)\, e^{j(\omega t + 3x + 4y)}$ V/m
(B) $(-8\boldsymbol{a}_x + 6\boldsymbol{a}_y - 5\boldsymbol{a}_z)\, e^{j(\omega t + 3x + 4y)}$ V/m
(C) $(-8\boldsymbol{a}_x - 6\boldsymbol{a}_y - 5\boldsymbol{a}_z)\, e^{j(\omega t - 3x - 4y)}$ V/m
(D) $(-8\boldsymbol{a}_x + 6\boldsymbol{a}_y - 5\boldsymbol{a}_z)\, e^{j(\omega t - 3x - 4y)}$ V/m

MCQ 7.4.2 The electric field of a uniform plane electromagnetic wave in free space, along the positive x direction is given by $\boldsymbol{E} = 10(\boldsymbol{a}_y + j\boldsymbol{a}_z)\, e^{-j25x}$. The frequency and polarization of the wave, respectively, are
(A) 1.2 GHz and left circular
(B) 4 Hz and left circular
(C) 1.2 GHz and right circular
(D) 4 Hz and right circular

MCQ 7.4.3 The electric field component of a time harmonic plane EM wave traveling in a nonmagnetic lossless dielectric medium has an amplitude of 1 V/m. If the relative permittivity of the medium is 4, the magnitude of the time-average power density vector (in W/m^2) is
(A) $\frac{1}{30\pi}$ (B) $\frac{1}{60\pi}$
(C) $\frac{1}{120\pi}$ (D) $\frac{1}{240\pi}$

MCQ 7.4.4 A plane wave having the electric field components $\boldsymbol{E}_i = 24\cos(3\times 10^8 - \beta y)\boldsymbol{a}_x$ V/m and traveling in free space is incident normally on a lossless medium with $\mu = \mu_0$ and $\varepsilon = 9\varepsilon_0$ which occupies the region $y \ge 0$. The reflected magnetic field component is given by
(A) $\frac{1}{10\pi}\cos(3\times 10^8 t + y)\,\boldsymbol{a}_x$ A/m
(B) $\frac{1}{20\pi}\cos(3\times 10^8 t + y)\,\boldsymbol{a}_x$ A/m
(C) $-\frac{1}{20\pi}\cos(3\times 10^8 t + y)\,\boldsymbol{a}_x$ A/m
(D) $-\frac{1}{10\pi}\cos(3\times 10^8 t + y)\,\boldsymbol{a}_x$ A/m

MCQ 7.4.5 A uniform plane wave in the free space is normally incident on an infinitely thick dielectric slab (dielectric constant $\varepsilon_r = 9$). The magnitude of the reflection coefficient is
(A) 0
(B) 0.3
(C) 0.5
(D) 0.8

MCQ 7.4.6 A plane wave of wavelength λ is traveling in a direction making an angle 30° with positive x-axis and 90° with positive y-axis. The $\boldsymbol{E}$ field of the plane wave can be represented as (E_0 is constant)

(A) $\boldsymbol{E} = \boldsymbol{a}_y E_0 e^{j\left(\omega t - \frac{\sqrt{3}\pi}{\lambda}x - \frac{\pi}{\lambda}z\right)}$

(B) $\boldsymbol{E} = \boldsymbol{a}_y E_0 e^{j\left(\omega t - \frac{\pi}{\lambda}x - \frac{\sqrt{3}\pi}{\lambda}z\right)}$

(C) $\boldsymbol{E} = \boldsymbol{a}_y E_0 e^{j\left(\omega t + \frac{\sqrt{3}\pi}{\lambda}x + \frac{\pi}{\lambda}z\right)}$

(D) $\boldsymbol{E} = \boldsymbol{a}_y E_0 e^{j\left(\omega t - \frac{\pi}{\lambda}x + \frac{\sqrt{3}\pi}{\lambda}z\right)}$

MCQ 7.4.7 The $\boldsymbol{H}$ field (in A/m) of a plane wave propagating in free space is given by

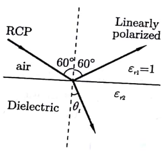
$$\boldsymbol{H} = \boldsymbol{a}_x \frac{5\sqrt{3}}{\eta_0}\cos(\omega t - \beta z) + \boldsymbol{a}_y\left(\omega t - \beta z + \frac{\pi}{2}\right).$$

The time average power flow density in Watts is

(A) $\frac{\eta_0}{100}$ (B) $\frac{100}{\eta_0}$

(C) $50\eta_0^2$ (D) $\frac{50}{\eta_0}$

MCQ 7.4.8 A right circularly polarized (RCP) plane wave is incident at an angle 60° to the normal, on an air-dielectric interface. If the reflected wave is linearly polarized, the relative dielectric constant ε_{r2} is



(A) $\sqrt{2}$ (B) $\sqrt{3}$

(C) 2 (D) 3

MCQ 7.4.9 When a plane wave traveling in free-space is incident normally on a medium having $\varepsilon_r = 4.0$ then the fraction of power transmitted into the medium is given by

(A) $\frac{8}{9}$ (B) $\frac{1}{2}$

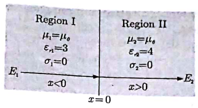
(C) $\frac{1}{3}$ (D) $\frac{5}{6}$

MCQ 7.4.10 A medium of relative permittivity $\varepsilon_{r2} = 2$ forms an interface with free-space. A point source of electromagnetic energy is located in the medium at a depth of 1 meter from the interface. Due to the total internal reflection, the transmitted beam has a circular cross-section over the interface. The area of the beam cross-section at the interface is given by

(A) 2π m² (B) π^2 m²

(C) $\frac{\pi}{2}$ m² (D) π m²

MCQ 7.4.11 A medium is divided into regions I and II about $x = 0$ plane, as shown in the figure below.



An electromagnetic wave with electric field $E_1 = 4\boldsymbol{a}_x + 3\boldsymbol{a}_y + 5\boldsymbol{a}_z$ is incident normally on the interface from region I. The electric file E_2 in region II at the interface is

(A) $E_2 = E_1$ (B) $4\boldsymbol{a}_x + 0.75\boldsymbol{a}_y - 1.25\boldsymbol{a}_z$

(C) $3\boldsymbol{a}_x + 3\boldsymbol{a}_y + 5\boldsymbol{a}_z$ (D) $-3\boldsymbol{a}_x + 3\boldsymbol{a}_y + 5\boldsymbol{a}_z$

MCQ 7.4.12 The magnetic field intensity vector of a plane wave is given by

$$\boldsymbol{H}(x, y, z, t) = 10\sin(50000t + 0.004x + 30)\,\boldsymbol{a}_y$$

where $\boldsymbol{a}_y$, denotes the unit vector in y direction. The wave is propagating with a phase velocity.

(A) 5×10^4 m/s (B) -3×10^8 m/s

(C) -1.25×10^7 m/s (D) 3×10^8 m/s

MCQ 7.4.13 Refractive index of glass is 1.5. Find the wavelength of a beam of light with frequency of 10^{14} Hz in glass. Assume velocity of light is 3×10^8 m/s in vacuum

(A) 3 μm (B) 3 mm

(C) 2 μm (D) 1 mm

MCQ 7.4.14 If $\boldsymbol{E} = (\boldsymbol{a}_x + j\boldsymbol{a}_y)\,e^{jkz - k\omega t}$ and $\boldsymbol{H} = (k/\omega\mu)(\boldsymbol{a}_y + j\boldsymbol{a}_x)\,e^{jkz - j\omega t}$, the time-averaged Poynting vector is

(A) null vector (B) $(k/\omega\mu)\,\boldsymbol{a}_z$

(C) $(2k/\omega\mu)\,\boldsymbol{a}_z$ (D) $(k/2\omega\mu)\,\boldsymbol{a}_z$

MCQ 7.4.15 A plane electromagnetic wave propagating in free space is incident normally on a large slab of loss-less, non-magnetic, dielectric material with $\varepsilon > \varepsilon_0$. Maxima and minima are observed when the electric field is measured in front of the slab. The maximum electric field is found to be 5 times the minimum field. The intrinsic impedance of the medium should be

(A) $120\pi\,\Omega$ (B) $60\pi\,\Omega$

(C) $600\pi\,\Omega$ (D) $24\pi\,\Omega$

MCQ 7.4.16 The depth of penetration of electromagnetic wave in a medium having conductivity σ at a frequency of 1 MHz is 25 cm. The depth of penetration at a frequency of 4 MHz will be

(A) 6.25 dm (B) 12.50 cm

(C) 50.00 cm (D) 100.00 cm

MCQ 7.4.17 A uniform plane wave traveling in air is incident on the plane boundary between air and another dielectric medium with $\varepsilon_r = 4$. The reflection coefficient for the normal incidence, is

(A) zero (B) $0.5\angle 180^\circ$

(B) $0.333\angle 0^\circ$ (D) $0.333\angle 180^\circ$

MCQ 7.4.18 If the electric field intensity associated with a uniform plane electromagnetic wave traveling in a perfect dielectric medium is given by $E(z,t) = 10\cos(2\pi 10^7 t - 0.1\pi z)$ V/m, then the velocity of the traveling wave is
(A) 3.00×10^8 m/sec
(B) 2.00×10^8 m/sec
(C) 6.28×10^7 m/sec
(D) 2.00×10^7 m/sec

MCQ 7.4.19 A plane wave is characterized by $E = (0.5a_x + a_y e^{j\pi/2})e^{j\omega t - jkz}$. This wave is
(A) linearly polarized
(B) circularly polarized
(C) elliptically polarized
(D) unpolarized

MCQ 7.4.20 Distilled water at 25°C is characterized by $\sigma = 1.7 \times 10^{-4}$ mho/m and $\varepsilon = 78\varepsilon_o$ at a frequency of 3 GHz. Its loss tangent $\tan\delta$ is ($\varepsilon = \frac{10^{-9}}{36\pi}$ F/m)
(A) 1.3×10^{-5}
(B) 1.3×10^{-3}
(C) $1.3 \times 10^{-4}/78$
(D) $1.3 \times 10^{-5}/78\varepsilon_0$

MCQ 7.4.21 A material has conductivity of 10^{-2} mho/m and a relative permittivity of 4. The frequency at which the conduction current in the medium is equal to the displacement current is
(A) 45 MHz
(B) 90 MHz
(C) 450 MHz
(D) 900 MHz

MCQ 7.4.22 A uniform plane electromagnetic wave incident on a plane surface of a dielectric material is reflected with a VSWR of 3. What is the percentage of incident power that is reflected ?
(A) 10%
(B) 25%
(C) 50%
(D) 75%

MCQ 7.4.23 A uniform plane wave in air impinges at 45° angle on a lossless dielectric material with dielectric constant ε_r. The transmitted wave propagates is a 30° direction with respect to the normal. The value of ε_r is
(A) 1.5
(B) $\sqrt{1.5}$
(C) 2
(D) $\sqrt{2}$

MCQ 7.4.24 Two coaxial cable 1 and 2 are filled with different dielectric constants ε_{r1} and ε_{r2} respectively. The ratio of the wavelength in the cables (λ_1/λ_2) is
(A) $\sqrt{\varepsilon_{r1}/\varepsilon_{r2}}$
(B) $\sqrt{\varepsilon_{r2}/\varepsilon_{r1}}$
(C) $\varepsilon_{r1}/\varepsilon_{r2}$
(D) $\varepsilon_{r2}/\varepsilon_{r1}$

MCQ 7.4.25 Identify which one of the following will NOT satisfy the wave equation.
(A) $50e^{j(\omega t - 3z)}$
(B) $\sin[\omega(10z + 5t)]$
(C) $\cos(y^2 + 5t)$
(D) $\sin(x)\cos(t)$

MCQ 7.4.26 A plane wave propagating through a medium $[\varepsilon_r = 8, v_r = 2, \text{and } \sigma = 0]$ has its electric field given by $E = 0.5Xe^{-(z/3)}\sin(10^8 t - \beta z)$ V/m. The wave impedance, in ohms is
(A) 377
(B) $198.5\angle 180°$
(C) $182.9\angle 14°$
(D) 183.4

MCQ 7.4.27 The time average poynting vector, in W/m², for a wave with $E = 24e^{j(\omega t + \beta z)}a_y$ V/m in free space is
(A) $-\frac{2.4}{\pi}a_z$
(B) $\frac{2.4}{\pi}a_z$
(C) $\frac{4.8}{\pi}a_z$
(D) $-\frac{4.8}{\pi}a_z$

MCQ 7.4.28 The wavelength of a wave with propagation constant $(0.1\pi + j0.2\pi)\,\text{m}^{-1}$ is
(A) $\frac{2}{\sqrt{0.05}}$ m
(B) 10 m
(C) 20 m
(D) 30 m

MCQ 7.4.29 The skin depth at 10 MHz for a conductor is 1 cm. The phase velocity of an electromagnetic wave in the conductor at 1,000 MHz is about
(A) 6×10^6 m/sec
(B) 6×10^7 m/sec
(C) 3×10^8 m/sec
(D) 6×10^8 m/sec

MCQ 7.4.30 A uniform plane wave in air is normally incident on infinitely thick slab. If the refractive index of the glass slab is 1.5, then the percentage of incident power that is reflected from the air-glass interface is
(A) 0%
(B) 4%
(C) 20%
(D) 100%

MCQ 7.4.31 Some unknown material has a conductivity of 10^6 mho/m and a permeability of $4\pi \times 10^{-7}$ H/m. The skin depth for the material at 1 GHz is
(A) 15.9 μm
(B) 20.9 μm
(C) 25.9 μm
(D) 30.9 μm

MCQ 7.4.32 The plane wave travelling in a medium of $\varepsilon_r = 1$, $\mu_r = 1$ (free space) has an electric field intensity of $100\sqrt{\pi}$ V/m. Determine the total energy density of this field.
(A) 13.9 nJ/m³
(B) 27.8 nJ/m³
(C) 139 nJ/m³
(D) 278 nJ/m³

MCQ 7.4.33 For a plane wave propagating in an unbounded medium (say, free space), the minimum angle between electric field and magnetic field vectors is
(A) 0°
(B) 60°
(C) 90°
(D) 180°

MCQ 7.4.34 For no reflection condition, a vertically polarized wave should be incident at the interface between two dielectrics having $\varepsilon_1 = 4$ and $\varepsilon_2 = 9$, with an incident angle of
(A) $\tan^{-1}\left(\frac{9}{4}\right)$
(B) $\tan^{-1}\left(\frac{3}{2}\right)$
(C) $\tan^{-1}\left(\frac{2}{3}\right)$
(D) $\tan^{-1}\left(\frac{4}{9}\right)$

MCQ 7.4.35 The electric field component of a wave in free space is given by

$$E = 10\cos(10^7 t + kZ)\,a_y \text{ V/m}$$

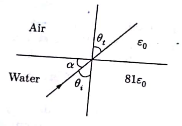
Following is a list of possible inferences :
1. Wave propagates along a_y
2. Wavelength $\lambda = 188.5$ m
3. Wave amplitude is 10 V/m

4. Wave number $= 0.33$ rad/m
5. Wave attenuates as it travels

Which of these inferences can be drawn from E ?

(A) 1, 2, 3, 4 and 5
(B) 2 and 3 only
(C) 3 and 4 only
(D) 4 and 5 only

MCQ 7.4.36 A plane wave is generated under water ($\varepsilon = 81\varepsilon_0$ and $\mu = \mu_0$). The wave is parallel polarized. At the interface between water and air, the angle α for which there is no reflection is



(A) 83.88°
(B) 83.66°
(C) 84.86°
(D) 84.08°

• **MCQ 7.4.37** An elliptically polarized wave travelling in the positive z-direction in air has x and y components

$$E_x = 3\sin(\omega t - \beta z)\ \text{V/m}$$
$$E_y = 6\sin(\omega t - \beta z + 75°)\ \text{V/m}$$

If the characteristic impedance of air is 360 Ω, the average power per unit area conveyed by the wave is

(A) 8 W/m²
(B) 4 W/m²
(C) 62.5 mW/m²
(D) 125 mW/m²

• **MCQ 7.4.38** The intrinsic impedance of copper at 3 GHz (with parameters : $\mu = 4\pi \times 10^{-7}$ H/m; $\varepsilon = 10^{-79}/36\pi$; and $\sigma = 5.8 \times 10^7$ mho/m) will be

(A) $0.02e^{j\pi/4}$ ohm
(B) $0.02e^{j\pi/2}$ ohm
(C) $0.2e^{j\pi/2}$ ohm
(D) $0.2e^{j\pi/4}$ ohm

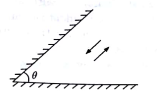
MCQ 7.4.39 In which direction is the plane wave $\boldsymbol{E} = 50\sin(10^8 t + 2z)\boldsymbol{a}_y$ V/m, (where $\boldsymbol{a}_y$ is the unit vector in y-direction), travelling ?

(A) along y direction
(B) along-y direction
(C) along z direction
(D) along-z direction

MCQ 7.4.40 If $\boldsymbol{E} = (\boldsymbol{a}_x + j\boldsymbol{a}_y)e^{-j\beta z}$, then the wave is said to be which one of the following ?

(A) Right circularly polarized
(B) Right elliptically polarized
(C) Left circularly polarized
(D) Left elliptically polarized

MCQ 7.4.41



What must be angle θ of a corner reflector, such that an incident wave is reflected in the same direction ?

(A) 30°
(B) 45°
(C) 60°
(D) 90°

MCQ 7.4.42 Which one of the following statements is correct ?

A right circularly polarised wave is incident from air onto a polystyrene ($\varepsilon_r = 2.7$). The reflected wave is

(A) right circularly polarised
(B) left circularly polarised
(C) right elliptically polarised
(D) left elliptically polarised

MCQ 7.4.43 The electric field of a wave propagating through a lossless medium ($\mu_0, 81\varepsilon_0$) is $\boldsymbol{E} = 10\cos(6\pi \times 10^8 t - bx)\overline{a}_y$

What is the phase constant β of the wave ?

(A) 2π rad/m
(B) 9π rad/m
(C) 18π rad/m
(D) 81 rad/m

MCQ 7.4.44 If the phase velocity of a plane wave in a perfect dielectric is 0.4 times its value in free space, then what is the relative permittivity of the dielectric ?

(A) 6.25
(B) 4.25
(C) 2.5
(D) 1.25

MCQ 7.4.45 In free space $\boldsymbol{E}(x,t) = 60(\omega t - 2x)\boldsymbol{a}_y$ V/m. What is the average power crossing a circular area of radius 4 m in the plane $x =$ constant ?

(A) 480 W
(B) 240 W
(C) 120 W
(D) 60 W

• **MCQ 7.4.46** A plane electromagnetic wave travelling in a perfect dielectric medium of intrinsic impedance η_1 is incident normally on its boundary with another perfect dielectric medium of characteristic impedance η_2. The electric and magnetic field strengths of the incident wave are denoted by E_i and H_i respectively whereas E_r and H_r denote these quantities for the reflected wave, and E_t and H_t for the transmitted wave.

Which of the following relations are correct ?

1. $E_i = \eta_1 H_i$
2. $E_r = \eta_1 H_r$
3. $E_t = \eta_2 H_t$

Select the correct answer using the codes given below

(A) 1, 2 and 3
(B) 1 and 2
(C) 1 and 3
(D) 2 and 3

MCQ 7.4.47 A plane electromagnetic wave travelling in a perfect dielectric medium of dielectric constant ε_1 is incident on its boundary with another perfect dielectric medium of dielectric constant ε_2. The incident ray makes an angle of θ_1 with the normal to the boundary surface. The ray transmitted into the other medium makes an angle of θ_2 with the normal.
If $\varepsilon_1 = 2\varepsilon_2$ and $\theta_1 = 60°$, which one of the following is correct ?
(A) $\theta_2 = 45°$
(B) $\theta_2 = \sin^{-1}0.433$
(C) $q_2 = \sin^{-1}0.612$
(D) There will be no transmitted wave

MCQ 7.4.48 Match List I (Nature of Polarization) with List II (Relationship Between X and Y Components) for a propagating wave having cross-section in the XY plane and propagating along z-direction and select the correct answer :

List-I	List-II
a. Linear	1. X and Y components are in same phase
b. Left circular	2. X and Y components have arbitrary phase difference
c. Right circular	3. X component leads Y by 90°
d. Elliptical	4. X component lags behind Y by 90°

Codes :

	a	b	c	d
(A)	1	4	2	3
(B)	4	1	2	3
(C)	1	4	3	2
(D)	4	1	3	2

MCQ 7.4.49 Match List I with List II and select the correct answer :

List-I	List-II
a. Propagation constant	1. $\sqrt{\omega\mu\sigma/2}$
b. Radiation intensity	2. $\frac{r^2}{2\eta}(E^2)$
c. Wave impedance	3. E_t/H_t
	4. $\boldsymbol{E}\times\boldsymbol{H}$

Codes :

	a	b	c
(A)	1	2	3
(B)	4	3	2
(C)	1	3	2
(D)	4	2	3

MCQ 7.4.50 **Assertion (A) :** For an EM wave normally incident on a conductor surface the magnetic field $\boldsymbol{H}$ undergoes a 180° phase reversal and the phase of electric field $\boldsymbol{E}$ remains same.
Reason (R) : The direction of propagation of incident wave will reverse after striking a conductor surface.
(A) Both A and R are true and R is the correct explanation of A
(B) Both A and R are true but R is NOT the correct explanation of A
(C) A is true but R is false
(D) A is false but R is true

MCQ 7.4.51 If the $\boldsymbol{E}$ field of a plane polarized EM wave travelling in the z-direction is :
$\boldsymbol{E} = \boldsymbol{a}_x E_x + \boldsymbol{a}_y E_y$ then its $\boldsymbol{H}$ field is :
(A) $\boldsymbol{a}_y \frac{E_x}{Z_0} - \boldsymbol{a}_x \frac{E_y}{Z_0}$
(B) $\boldsymbol{a}_y \frac{E_x}{Z_0} + \boldsymbol{a}_x \frac{E_y}{Z_0}$
(C) $\boldsymbol{a}_x \frac{E_y}{Z_0} - \boldsymbol{a}_y \frac{E_x}{Z_0}$
(D) $-\boldsymbol{a}_x \frac{E_y}{Z_0} - \boldsymbol{a}_y \frac{E_x}{Z_0}$

MCQ 7.4.52 In a uniform plane wave, the value of E/H is
(A) $\sqrt{\mu/\varepsilon}$
(B) $\sqrt{\varepsilon/\mu}$
(C) 1
(D) $\sqrt{\mu\varepsilon}$

MCQ 7.4.53 The phenomenon of microwave signals following the curvature of earth is known as
(A) Faraday effect
(B) ducting
(C) wave tilt
(D) troposcatter

MCQ 7.4.54 Which one of the following statements is NOT correct for a plane wave with $\boldsymbol{H} = 0.5e^{-0.1x}\cos(10^6 t - 2x)\,\boldsymbol{a}_z$ A/m
(A) The wave frequency is 10^6 r.p.s
(B) The wavelength is 3.14 m
(C) The wave travels along $+\,x$-direction
(D) The wave is polarized in the z-direction

MCQ 7.4.55 The vector magnetic potential of a particular wave traveling in free space is given by $\boldsymbol{A} = \boldsymbol{a}_x A_x \sin(\omega t - \beta z)$ where A_x is a constant. The expression for the electric field will be
(A) $-\boldsymbol{a}_x \beta A_x \sin(\omega t - \beta z)$
(B) $-\boldsymbol{a}_y \beta A_x \sin(\omega t - \beta z)$
(C) $-\boldsymbol{a}_y \omega A_x \cos(\omega t - \beta z)$
(D) $-\boldsymbol{a}_x \omega A_x \cos(\omega t - \beta z)$

MCQ 7.4.56 In free space $\boldsymbol{H}$ field is given as $\boldsymbol{H}(z,t) = -\frac{1}{6\pi}\cos(\omega t + \beta z)\boldsymbol{a}_y$ $\boldsymbol{E}(z,t)$ is
(A) $20\cos(\omega t + \beta z)\boldsymbol{a}_x$
(B) $20\cos(\omega t + \beta z)\boldsymbol{a}_z$
(C) $20\sin(\omega t + \beta z)\boldsymbol{a}_y$
(D) $20\sin(\omega t + \beta z)\boldsymbol{a}_x$

MCQ 7.4.57 If electric field intensity phasor of an EM wave in free space is $\boldsymbol{E} = 10e^{-j4y}\boldsymbol{a}_x$ V/m.The angular frequency ω, in rad/s, is
(A) $4 \times 3 \times 10^8$
(B) $4y \times 3 \times 10^8$
(C) $t \times 3 \times 10^8$
(D) $10 \times 3 \times 10^8$

MCQ 7.4.58 **Assertion (A) :** Electromagnetic waves propagate being guided by parallel plate perfect conductor surface.
Reason (R) : Tangential component of electric field intensity and normal component of magnetic field intensity are zero on a perfect conductor surface.
(A) Both **Assertion (A)** and **Reason (R)** are individually true and **Reason (R)** is the correct explanation of **Assertion (A)**
(B) Both **Assertion (A)** and **Reason (R)** are individually true but **Reason (R)** is not the correct explanation of **Assertion (A)**
(C) **Assertion (A)** is true but **Reason (R)** is false
(D) **Assertion (A)** is false but **Reason (R)** is true

MCQ 7.4.59 A uniform plane wave is propagating in a material for which $\varepsilon = 4\varepsilon_0$, $\mu = 7\mu_0$ and $\sigma = 0$. The skin depth for the material is
(A) zero
(B) infinity
(C) 28 m
(D) 14 m

MCQ 7.4.60 Consider the following statements :
1. In conducting medium the field attenuates exponentially with increasing depth.
2. Conducting medium behaves like an open circuit to the electromagnetic field.
3. In lossless dielectric relaxation time is infinite.
4. In charge-free region, the Poisson's equation becomes Laplace's equation.

(A) 1, 2 and 3 only
(B) 1, 3 and 4 only
(C) 2, 3 and 4 only
(D) 1, 2, 3 and 4

MCQ 7.4.61 In free space

$$\boldsymbol{E}(Z,t) = 60\pi\cos(\omega t - \beta z)\boldsymbol{a}_x \text{ V/m}.$$

The average power crossing a circular area of π square metres in the plane z=constant is
(A) 16π watt/m^2
(B) 15π watt/m^2
(C) 14π watt/m^2
(D) 13π watt/m^2

MCQ 7.4.62 In free space

$$\boldsymbol{E}(Z,t) = 120\pi\cos(\omega t - \beta Z)\boldsymbol{a}_x \text{ Vm}^{-1}$$

What is the average power in Wm^{-2} ?
(A) $30\pi\boldsymbol{a}_z$
(B) $60\pi\boldsymbol{a}_z$
(C) $90\pi\boldsymbol{a}_z$
(D) $120\pi\boldsymbol{a}_z$

MCQ 7.4.63 The electric field of a uniform plane wave is given by :

$$\boldsymbol{E} = 10\sin(3\pi\times10^8t - \pi Z)\boldsymbol{a}_x + 10\cos(3\pi\times10^8t - \pi Z)\boldsymbol{a}_y \text{ Vm}^{-1}$$

What is the corresponding magnetic field $\boldsymbol{H}$
(A) $\frac{10}{377}\sin(3\pi\times10^8t - \pi Z)\boldsymbol{a}_y + \frac{10}{377}\cos(3\pi\times10^8t - \pi Z)(-\boldsymbol{a}_x)$ Am^{-1}
(B) $\frac{10}{377}\sin(3\pi\times10^8t - \pi Z)(-\boldsymbol{a}_y) + \frac{10}{377}\cos(3\pi\times10^8t - \pi Z) - (\boldsymbol{a}_x)$ Am^{-1}
(C) $\frac{10}{377}\sin(3\pi\times10^8t - \pi Z)\boldsymbol{a}_y + \frac{10}{377}\cos(3\pi\times10^8t - \pi Z)(\boldsymbol{a}_x)$ Am^{-1}
(D) $\frac{10}{377}\sin(3\pi\times10^8t - \pi Z)(-\boldsymbol{a}_y) + \frac{10}{377}\sin(3\pi\times10^8t - \pi Z)(-\boldsymbol{a}_x)$ Am^{-1}

MCQ 7.4.64 Consider the following statements in connection with electromagnetic waves :
1. Conducting medium behaves like an open circuit to the electromagnetic field.
2. At radio and microwave frequencies the relaxation time is much less than the period
3. In loss-less dielectric the relaxation time is finite.
4. Intrinsic impedance of a perfect dielectric medium is a pure resistance.

Which is these statements is/are correct ?
(A) 1 only
(B) 1 and 2 only
(C) 2 and 3 only
(D) 2, 3 and 4

MCQ 7.4.65 **Assertion (A) :** The velocity of electromagnetic waves is same is same as velocity of light.
Reason (R) : Electrons also travel with the same velocity as photons.
(A) Both A and R are true and R is the correct explanation of A
(B) Both A and R are true but R is not the correct explanation of A
(C) A is true but R is false
(D) A is false but R is true

MCQ 7.4.66 Which of the following is zero as applied to electromagnetic field ?
(A) grad div $\boldsymbol{A}$
(B) div grad V
(C) div curl $\boldsymbol{A}$
(D) curl curl $\boldsymbol{A}$

MCQ 7.4.67 What is the Poynting's vector on the surface of a long straight conductor of radius b and conductivity σ which carries current I in the z-direction ?
(A) $-\frac{I^2}{2\sigma\pi^2b^3}\boldsymbol{i}_r$
(B) $\frac{I^2}{2\sigma\pi^2b^2}\boldsymbol{i}_r$
(C) $\frac{I^2}{\sigma\pi b^2}\boldsymbol{i}_z$
(D) $\frac{I}{2\pi b}\boldsymbol{i}_\phi$

MCQ 7.4.68 Consider the following statements regarding EM wave
1. An EM wave incident on a perfect dielectric is partially transmitted and partially reflected
2. An EM wave incident on a perfect conductor is fully reflected
3. When an EM wave is incident from a more dense medium to less dense medium at an angle equal to or exceeding the critical angle, the wave suffers total internal reflection

Which of the statements given above are correct ?
(A) Only 1 and 2
(B) Only 2 and 3
(C) Only 1 and 3
(D) 1, 2 and 3

MCQ 7.4.69 A uniform plane wave has a wavelength of 2 cm in free space and 1 cm in a perfect dielectric. What is the relative permittivity of the dielectric ?
(A) 2.0
(B) 0.5
(C) 4.0
(D) 0.25

MCQ 7.4.70 With the increase in frequency of an electromagnetic wave in free space, how do the velocity v_e and characteristic impedance Z_e change ?
(A) v_e increase and Z_e decreases
(B) v_e decreases and Z_e increases
(C) Both v_e and Z_e increase
(D) Both v_e and Z_e remain unchanged

MCQ 7.4.71 The E field of a plane electromagnetic wave travelling in a non-magnetic non-conducting medium is given by $\boldsymbol{E} = \boldsymbol{a}_x 5\cos(10^9 t + 30Z)$. What is the dielectric constant of the medium ?
(A) 30
(B) 10
(C) 9
(D) 81

MCQ 7.4.72 In the wave equation $\nabla^2 \boldsymbol{E} = \mu\varepsilon \frac{\partial^2 \boldsymbol{E}}{\partial t^2} + \mu\sigma \frac{\partial \boldsymbol{E}}{\partial t}$ which term is responsible for attenuation of the wave ?
(A) $\nabla^2 \boldsymbol{E}$
(B) $\mu\varepsilon \frac{\partial^2 \boldsymbol{E}}{\partial t^2}$
(C) $\mu\sigma \frac{\partial \boldsymbol{E}}{\partial t}$
(D) All of the above three

MCQ 7.4.73 Consider the following statements :
1. Poisson's equation finds application in vaccum tube and gaseous discharge problems
2. Gauss's law is useful for determining field and potential distribution about bodies having unsymmetrical geometry.
3. For the propagation of electro-magnetic waves, the time varying electric fields must support time varying magnetic fields.
4. The unit of Poynting's vector is W/m^2

Which of the statements given above are correct ?
(A) 1, 2 and 3
(B) 1, 3 and 4
(C) 2, 3 and 4
(D) 1, 2 and 4

MCQ 7.4.74 What is the phase velocity of plane wave in a good conductor ?
(A) $\sqrt{\pi f \mu \sigma}$
(B) $\sqrt{\frac{\pi f \sigma}{(\mu\sigma)}}$
(C) $\sqrt{\frac{\pi f}{(\mu\sigma)}}$
(D) $2\sqrt{\frac{\pi f}{(\mu\sigma)}}$

MCQ 7.4.75 The instantaneous electric field of a plane wave propagating in z-direction is
$$\boldsymbol{E}(t) = [\boldsymbol{a}_x E_1 \cos\omega t - \boldsymbol{a}_y E_2 \sin\omega t] e^{-jkz}$$
This wave is
(A) Linearly polarised
(B) Elliptically polarised
(C) Right hand circularly polarised
(D) Left hand circularly polarised

MCQ 7.4.76 **Assertion (A) :** Skin depth is the depth by which electromagnetic wave has been increased to 37% of its original value.
Reason (R) : The depth of penetration of wave in a lossy dielectric increases with increasing wavelength.
(A) Both A and R are true and R is the correct explanation of A
(B) Both A and R are true but R is NOT the correct explanation of A
(C) A is true but R is false
(D) A is false but R is true

MCQ 7.4.77 Which one of the following is the correct electromagnetic wave equation in terms of vector potential $\boldsymbol{A}$?
(A) $\nabla^2 \boldsymbol{A} - \frac{\partial^2 \boldsymbol{A}}{\partial t^2} = -\boldsymbol{J}$
(B) $\nabla^2 \boldsymbol{A} - \frac{\mu}{\varepsilon}\frac{\partial^2 \boldsymbol{A}}{\partial t^2} = -\mu \boldsymbol{J}$
(C) $\nabla^2 \boldsymbol{A} - \frac{\partial^2 \boldsymbol{A}}{\partial t^2} = -\mu \boldsymbol{J}$
(D) $\nabla^2 \boldsymbol{A} - \mu\varepsilon\frac{\partial^2 \boldsymbol{A}}{\partial t^2} = -\mu \boldsymbol{J}$

MCQ 7.4.78 Which one of the following statements is correct ? The wavelength of a wave propagating in a wave guide is
(A) smaller than the free space wavelength
(B) greater than the free space wavelength
(C) directly proportional to the group velocity
(D) inversely proportional to the phase velocity

MCQ 7.4.79 Which one of the following statements is correct ? For a lossless dielectric medium, the phase constant for a travelling wave, β is proportional to
(A) ε_r
(B) $\sqrt{\varepsilon_r}$
(C) $1/\varepsilon_r$
(D) $1/\sqrt{\varepsilon_r}$

MCQ 7.4.80 In a lossless medium the intrinsic impedance $\eta = 60\pi$ and $\mu_r = 1$. What is the value of the dielectric constant ε_r ?
(A) 2
(B) 1
(C) 4
(D) 8

MCQ 7.4.81 An electromagnetic field is said to be conservative when
(A) $\nabla^2 E = \mu\varepsilon(\partial^2 E/\partial t^2)$
(B) $\nabla^2 H = \mu\varepsilon(\partial^2 H/\partial t^2)$
(C) Curl on the field is zero
(D) Divergence of the field is zero

MCQ 7.4.82 Given that $\boldsymbol{H} = 0.5\exp[-0.1x]\sin(10^6 t - 2x)\,\boldsymbol{a}_z$ (A/m), which one of the following statements is not correct ?
(A) Wave is linearly polarized along $\boldsymbol{a}_z$
(B) The velocity of the wave is 5×10^5 m/s
(C) The complex propagation constant is $(0.1 + j2)$
(D) The wave is traveling along $\boldsymbol{a}_z$

MCQ 7.4.83 For a conducting medium with conductivity σ, permeability μ, and permittivity ε, the skin depth for an electromagnetic signal at an angular frequency ω is proportional to
(A) σ
(B) $1/\omega$
(C) $1/\sqrt{\sigma}$
(D) $1/\mu$

MCQ 7.4.84 The electric field of a uniform plane wave is given by $E = 10\sin(10\omega t - \pi z)\,\boldsymbol{a}_x + 10\cos(\omega t - \pi z)\,\boldsymbol{a}_y$ (V/m)
The polarization of the wave is
(A) Circular
(B) Elliptical
(C) Linear
(D) Undefined

MCQ 7.4.85 In free space $\boldsymbol{H}(z,t) = 0.10\cos(4\times10^7 t - \beta z)\,a_x$ A/m. The expression for $\boldsymbol{E}(z,t)$ is
(A) $\boldsymbol{E}(z,t) = 37.7\cos(4\times10^7 t - \beta z)\,a_y$
(B) $\boldsymbol{E}(z,t) = 2.65\times10\cos(4\times10^7 t - \beta z)\,a_z$
(C) $\boldsymbol{E}(z,t) = 37.7\cos(4\times10^7 t - \beta z)\,a_x$
(D) $\boldsymbol{E}(z,t) = -37.7\cos(4\times10^7 t - \beta z)\,a_y$

MCQ 7.4.86 A plane wave whose electric field is given by $\boldsymbol{E} = 100\cos(\omega t - 6\pi x)\,\boldsymbol{a}_z$ passes normally from a material 'A' having $\varepsilon_r = 4$, $\mu_r = 1$ and $\sigma = 0$ to a material 'B' having $\varepsilon_r = 9$, $\mu_r = 4$ and $\sigma = 0$. Match items in **List I** with **List II** and select the correct answer :

	List I		List II
a	Intrinsic impedance of medium 'B'	1.	6π
b	Reflection coefficient	2.	80π
c	Transmission coefficient	3.	1/7
d	Phase shift constant of medium 'A'	4.	8/7

Codes :

	a	b	c	d
(A)	4	1	2	3
(B)	2	3	4	1
(C)	4	3	2	1
(D)	2	1	4	3

MCQ 7.4.87 In free space $\boldsymbol{E}(z,t) = 50\cos(\omega t - \beta z)\,\boldsymbol{a}_x$ V/m and $\boldsymbol{H}(z,t) = 5/12\pi\cos(\omega t - \beta z)\,\boldsymbol{a}_y$ A/m. The average power crossing a circular area of radius $\sqrt{24}$ m in plane $z =$ constant is
(A) 200 W
(B) 250 W
(C) 300 W
(D) 350 W

MCQ 7.4.88 Consider a plane electromagnetic wave incident normally on the surface of a good conductor. The wave has an electric field of amplitude 1 V/m and the skin depth for the conductor is 10 cm.
Assertion (A) : The amplitude of electric field is $(1/e^2)$ (V/m) after the wave has travelled a distance of 20 cm in the conductor.
Reason (R) : Skin depth is the distance in which the wave amplitude decays to (1/e) of its value at the surface.
(A) Both A and R are true and R is the correct explanation of A
(B) Both A and R are true but R is NOT the correct explanation of A

(C) A is true but R is false
(D) A is false but R is true

MCQ 7.4.89 Three media are characterised by
1. $\varepsilon_r = 8, \mu_r = 2, \sigma = 0$
2. $\varepsilon_r = 1, \mu_r = 9, \sigma = 0$
3. $\varepsilon_r = 4, \mu_r = 4, \sigma = 0$

ε_r is relative permittivity, μ_r is relative permeability and σ is conductivity. The value of the intrinsic impedances of the media 1, 2 and 3 respectively are
(A) 188 Ω, 377 Ω and 1131 Ω
(B) 377 Ω, 1131 Ω and 188 Ω
(C) 188 Ω, 1131 Ω, and 377 Ω
(D) 1131 Ω, 188 Ω, and 377 Ω

MCQ 7.4.90 A plane EM wave $(\boldsymbol{E}_i, \boldsymbol{H}_i)$ travelling in a perfect dielectric medium of surge impedance 'Z' strikes normally on an infinite perfect dielectric medium of surge impedance $2Z$. If the refracted EM wave is $(\boldsymbol{E}_r, \boldsymbol{H}_r)$, the ratios of E_i/E_r and H_i/H_r are respectively
(A) 3 and -3
(B) 3/2 and 1/3
(C) 3/4 and 3/2
(D) 3/4 and 2/3

MCQ 7.4.91 For a perfect conductor, the field strength at a distance equal to the skin depth is X% of the field strength at its surface. The value 'X%' is
(A) Zero
(B) 50%
(C) 36%
(D) 26%

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